Test Methods for Evaluating Field Performance of RWIS Sensors

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Test Methods for Evaluating Field Performance of RWIS Sensors

Prepared for:

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TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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ABSTRACT

Transportation agencies are increasingly dependent on data from Road Weather Information Systems (RWIS) for their snow and ice control operations. However, uncertainty in data accuracy of RWIS Environmental Sensor Station (ESS) sensors can make users question the value of the information. While testing and calibration methods for ESS *atmospheric* sensors are available in existing literature, no such effort has been undertaken for *pavement* sensors. This research project fills the need by developing testing methods for pavement sensors and it seeks to establish guidelines for practical testing methods that will evaluate whether the pavement sensor is providing an accurate representation of actual conditions at the installed site.

This Final Report presents the findings of the research project that has developed test protocols, conducted tests and analyzed and documented the results of laboratory validation testing to measure various performance parameters of pavement sensors. Field tests were conducted in Minnesota, Nevada and Pennsylvania and the results were incorporated into this Final Report and the Field Test Procedures for Environmental Sensor Stations.

LIST OF ACRONYMS

Acronym	Meaning
ASOS	Automated Surface Observing System
ASTM	American Society of Testing Materials
AWOS	Automated Weather Observing Systems
CRRL	U.S. Army Cold Regions Research & Engineering Laboratory
DOT	Department of Transportation
EPA	United States Environmental Protection Agency
ESS	Environmental Sensor Station
FAA	Federal Aviation Administration
FSL	Forecast Systems Laboratory
IR	Infrared
NCHRP	National Cooperative Highway Research Program
NTCIP	National Transportation Communications for ITS Protocol
NWS	National Weather Service
PIARC	Permanent International Association of Road Congresses
QC	Quality Control
RPU	Remote Processor Unit
RWIS	Road Weather Information Systems
SAE	Society of Automotive Engineers
SIRWEC	Standing International Road Weather Commission
SNRA	Swedish National Road Administration
TRB	Transportation Research Board
TRIS	Transportation Research Information Services
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

INTRODUCTION

Transportation agencies are increasingly dependent on data from Road Weather Information Systems (RWIS) for making decisions regarding their snow and ice control operations. However, uncertainty in the accuracy of data generated by RWIS Environmental Sensor Station (ESS) sensors can make users question the value of the information. While testing and calibration methods for ESS *atmospheric* sensors are available in existing literature, no such effort has been undertaken for *pavement* sensors. This research project fills this need by developing testing methods for pavement sensors, and establishing guidelines for practical testing methods that will evaluate whether a pavement sensor is providing an accurate representation of actual conditions at the installed site.

Currently, most transportation agencies using ESS sensors rely on vendor-developed testing methods, or they accept the sensor data without regular testing. NCHRP has determined that practical guidelines are needed for testing ESS sensors to evaluate whether a sensor is accurately representing actual conditions at the installed site.

This research project was undertaken to develop standard field test procedures for in-place pavement sensors. The research project does not include testing of ESS atmospheric sensors, but information for testing atmospheric sensors has been researched in existing sources and is included in the Field Test Procedures for Environmental Sensor Stations, the separately published document that provides the field testing procedures for pavement sensors.

The research project has developed test protocols, conducted tests and analyzed and documented the results of laboratory and field validation testing to measure various performance parameters of pavement sensors.

Note: Originally, this research project also included developing methods for the field calibration of pavement sensors. However, early in the research and during discussions with pavement sensor manufacturers, it was determined that pavement sensor calibration was either a factory setting or not available. Therefore, it was decided that pavement sensor calibration could not be applied to a field testing operation.

RESEARCH APPROACH

In order to develop the knowledge base for the research project, an extensive literature search was conducted, and key experts from around the world were interviewed to document the prior work that has been done in the area of ESS sensor testing and calibration procedures.

Stakeholder organizations were surveyed to determine their accuracy requirements for pavement temperature and surface condition data. Information was also collected about the level of complexity that each agency could accommodate when testing its ESS equipment. Respondents unanimously supported the idea of having standardized testing procedures available. However, most respondents said that, in order for the procedure to be practical, it should require two hours or less per site to complete. Additionally, most respondents said that the total training required for testing procedures would need to be less than two days. This result strongly suggests that any procedure selected for use must be both easy to learn and simple to carry out in the field to be acceptable to RWIS users.

The stakeholder survey also provided valuable information about the types of sensors used. All of the respondents used surface temperature sensors, indicating that developing a procedure for this type of sensor should be a priority. Subsurface temperature and salinity/freezing point sensors were also common. Surface moisture sensors were used by roughly half of the respondents.

A matrix of various possible field testing procedures was developed for measuring pavement surface and subsurface temperature, sensor moisture state and freezing point temperature. This matrix quantified the effectiveness of the various field testing procedures so that the most promising methods could be developed. Statistical methods were used to design the experiments and analyze the effect of sensor type on the testing methods.

The matrix identified the most promising pavement sensor evaluation procedures that could be implemented by field personnel. Those procedures were then subjected to laboratory validation testing in a controlled laboratory to obtain accurate and reproducible results.

Laboratory tests were performed on six passive ESS sensors that were installed in both asphalt and concrete pavement test sections. One active ESS sensor was also installed in a separate concrete test section. Each test was conducted once, results compiled, and then reviewed by the project team. Following the validation test review, test procedures were modified as necessary and each test was conducted again.

Field tests were conducted in Minnesota, Nevada and Pennsylvania. Each state Department of Transportation provided technicians to conduct the tests. The technicians were trained by the research project team and were asked to perform the tests on local sensors. The technicians were observed during the testing process, and based on their findings, the test procedures were modified to improve the testing methods. The final testing methods are included in the Field Test Procedures for Environmental Sensor Stations.

A variety of baseline data collection approaches were also evaluated. For temperature, both non-contact baseline sensors (such as infrared guns) and contact baseline sensors (such as thermocouples and thermistors) were evaluated for their accuracy and ease of use. Lastly, the duration of each task, including baseline setup, cleaning, procedure steps, sensor stabilization, and final clean-up was documented.

RESULTS

The following results are drawn from laboratory and field tests. In some cases, the original testing procedure was modified to mitigate testing complications or to try different methods to understand the fundamental scientific processes involved in the tests.

For ambient pavement temperature tests, tests run at different temperatures revealed no significant accuracy difference. An ice bath can be placed on the pavement sensor to force the sensor to 32º F, but the bath must be constantly stirred for more than 20 minutes to depress the sensor temperature close to 32º F. Sensors with their temperature sensing elements two to five inches below the surface cannot be verified in this manner, because it is not reasonable to wait for the ice bath to cool the subsurface sensor down to 32º F. Also, dry ice can be used to cool the sensor, but this procedure is not approved by the sensor manufacturers and is therefore not recommended in the Field Test Procedures for Environmental Sensor Stations.

Another set of tests verifies that pavement sensors can correctly report surface state. In both laboratory and field tests, the tests showed that the pavement sensors could accurately report dry, wet and ice conditions, but were not necessarily as accurate in conditions where the weather did not match the surface state, such as a dry condition on a rainy day. In this situation, the atmospheric sensors sometimes overruled the pavement sensors. Frost can only be tested by verifying an existing condition because it is difficult to artificially produce frost.

For the freezing point, both active and passive sensors can be tested, although passive sensors should be tested at a four percent concentration for increased accuracy. The four sensor models analyzed in the laboratory were especially sensitive to the film thickness are generally not available for field testing in the United States. Active sensors produce excellent results, but take longer to test because they must run through a physical process before giving an updated reading. Most freezing point sensors require testing to be performed not many degrees warmer than water's freezing point, although some software can be configured to report the freezing point at any temperature.

CONCLUSIONS

The results of this investigation provided a sound basis for assessing the adequacy of the developed test methodologies for ESS pavement sensors and determined the availability of information for atmospheric sensors. Based on these findings, the following major conclusions and recommendations are offered.

It is feasible to run the temperature tests on pavement sensors that have their temperature sensor at the surface. It is not feasible to perform forced condition temperature tests with pavement sensors that have temperature sensors embedded below the surface of the pavement, as it takes too long to acclimate embedded sensors to the forced condition.

Surface state readings often require or are aided by atmospheric ESS data. If the atmospheric data is not available, such as in the laboratory studies, the condition may be misreported or not be as accurate as with the atmospheric sensors. If the field atmospheric sensors detect a different condition than the condition of the pavement sensor, the remote processing unit (RPU) will not necessarily report the correct pavement sensor surface state. Each sensor and each ESS station operates differently and must be researched before performing surface state tests.

The test procedures included in the Field Test Procedures for Environmental Sensor Stations have been thoroughly tested and proven to test sensor performance in both the laboratory and field. The procedures are simple to run and can quickly show if a sensor is properly calibrated. Though they are based on simple physical processes, these guidelines are robust enough to be run on a variety of sensors throughout the nation. By following these guidelines, agencies will be able to increase sensor performance.

CHAPTER 1
Introduction and Research Approach

RESEARCH PROBLEM STATEMENT

At least 42 state Departments of Transportation (DOTs) and other public and private sector agencies that use road weather information systems typically specify requirements for the accuracy of RWIS atmospheric, pavement surface, and subsurface sensor measurements at the time of procurement. Most agencies rely on vendor-developed testing and calibration methods or they accept the sensor data without regular and timely recalibration. This creates uncertainty in the accuracy of the data generated by the sensors and compromises the value of the information for use in decision-making. Guidelines are needed for practical testing and calibration methods for RWIS sensors that will evaluate whether sensors are accurately representing actual conditions at the installed sites.

Testing and calibration methods for RWIS atmospheric sensors are available in existing literature and practices. Therefore, the primary effort of this research project was the developing testing methods for RWIS pavement surface and subsurface sensors.

The National Transportation Communications for ITS Protocol (NTCIP) Standards Committee has established that a Remote Processing Unit (RPU) connected to one or more sensors for the collection of environmental or meteorological data is called an Environmental Sensor Station (ESS). A collection of RPUs and sensors connected to a central system for analysis and use by maintenance personnel is considered RWIS. Therefore, the remainder of this report will reference ESS sensors instead of RWIS sensors.

RESEARCH OBJECTIVE AND SCOPE

The research objective was to develop practical testing and calibration methods to obtain reliable operation of ESS pavement surface and subsurface sensors in field deployments. This study defines the equipment and develops the procedures that state, county and municipal personnel can use to test sensors with a comparative test between baseline data and sensor data. The standardized test procedures can be used nationwide on many types of sensors.

This research project has developed test protocols, conducted laboratory tests and completed field tests to measure various performance parameters of pavement sensors. The results of this research have been combined with existing methods for atmospheric sensors to provide practical guidelines for field testing and calibrating ESS sensors. These procedures and required testing equipment are documented and published in the Field Test Procedures for Environmental Sensor Stations so that stakeholders can apply these procedures to testing ESS sensors in their states. In addition, a Microsoft PowerPoint presentation is available to supplement the standalone guidelines.

RESEARCH APPROACH

To meet these objectives and produce the Field Test Procedures for Environmental Sensor Stations for testing ESS sensors in field deployment, the project team undertook several activities as outlined in the NCHRP problem statement:

1. Conducted an extensive literature search and interviewed key experts from around the world to document the prior work that has been done in the area of ESS sensor testing and calibration procedures.

2. Surveyed the stakeholder states to determine the required accuracy of pavement temperature, surface condition and subsurface moisture. During the survey, information was collected about the level of complexity that states are comfortable with when testing and calibrating their ESS equipment.

3. Developed a matrix of testing methods for various pavement sensor parameters. This matrix quantified the estimated effectiveness of the various testing methods. The most promising methods were developed for this research project.

4. Designed and validated various field testing procedures in a laboratory environment to determine the most promising testing methods for surface sensors.

The project team traveled to three states and trained public agency personnel to implement the test procedures. Those personnel performed the procedures and the field test plan was revised based on the lessons learned from the training and testing process. At the conclusion of the field testing, the ESS sensor testing methods that proved most promising were integrated into Field Test Procedures for Environmental Sensor Stations.

CHAPTER 2
Findings

In this section of the report, the results of the project activities are described. They include the review of relevant literature, summary of the stakeholder survey, matrix for testing procedures, laboratory validation test findings and field test findings.

BACKGROUND INFORMATION SEARCH

An extensive search was conducted to gather and summarize existing knowledge pertaining to both atmospheric and pavement ESS sensors. This included domestic and international sources of information, such as, RWIS users and manufacturers, certified installers, the Federal Aviation Administration (FAA), the National Weather Service (NWS) and the Society of Automotive Engineers (SAE). Key experts from around the world were contacted to document the prior work that has been done in the area of RWIS sensor testing.

Calibration involves measuring the conformance to or discrepancy from a specification for a device and an adjustment of the device to conform to the specification. It has been determined that pavement sensors may not be adjusted in the field. Because it is not possible to calibrate the sensors, it has been decided to only test the sensors. Therefore, calibration is not a part of the laboratory or field tests or the implementation procedures in the Field Test Procedures for Environmental Sensor Stations.

Literature Search

A review of the Transportation Research Board – Transportation Research Information Services (TRB-TRIS) and general search did not find relevant information on testing and calibrations methods for field procedures. However, inquiries of regulatory agencies' web sites produced a listing of publications that the agencies use in their operations. A number of those documents report their calibration methods for atmospheric sensors [2, 3, 4, 5, 6]. In addition, atmospheric sensor manufacturers have published testing and calibration procedures for a number of their sensors.

The search for information on pavement sensors did not yield much useful information. The research supplied a number of references to papers that were presented at international conferences, but papers presented at those conferences tended to be very brief and usually provided results. As a result, those papers could not provide information on testing procedures.

Two papers that concern the monitoring of pavement temperatures by in-pavement sensors were prepared by Ohio University [7] for Ohio DOT and SRF Consulting Group, Inc. [8] for the Aurora Consortium. A number of their procedures were incorporated in the validation laboratory testing procedures for this research project.

Transport Research Laboratory of England has determined that to test a pavement sensor for freezing point temperature, brine needs to be sprayed on the sensor [9]. By spraying the material, actual road conditions may be more accurately simulated. One vendor has a pavement sensor that has the capability to measure film thickness with an accuracy of 0.1 mm in the range of 0.0 to 1 mm and has an accuracy of better than 10 percent for salt concentration [10,11]. Another vendor that their sensor will determine a film thickness of wet pavement condition in the range of 0.1 to 0.5 mm of film thickness [12].

The FAA has issued an Advisory Circular [AC 150/5220-13B Runway Surface Condition Sensor Specification Guide (3/27/1991)] that provides guidance in preparing procurement specifications for sensor systems that monitor and report runway surface conditions [13]. The runway sensor specification requirement for surface temperature is to have an accuracy of ±0.278ºC (±0.5º F) and to detect the presence or absence of moisture. The manufacturer is to provide the airport, in writing, the results of tests establishing compliance with the applicable specifications. In addition the manufacturer agrees to maintain a testing/evaluation/quality control program for the equipment. There are no procedures to field test the sensor in the Advisory Circular.

In discussions with Mr. George Legarreta from the FAA concerning updating the FAA Advisory Circulars, it was indicated that it is the FAA's intent to cancel their Advisory Circular [AC 150/5220-13B *Runway Surface Condition Sensor Specification Guide*] because of a lack of resources to keep them updated. Instead the FAA would use industry standards developed by the SAE Aerospace Standard and refer to them in their Advisory Circulars.

The SAE G-15 Airport Snow and Ice Control Equipment Committee is working on replacing the old Advisory Circular [AC 150/5220-13B] with an SAE Aerospace Recommended Practice for Runway Weather Information Systems. Sensors included in the Recommended Practice are in-pavement surface sensors, subsurface probes and atmospheric sensors to monitor pavement surface conditions and atmospheric conditions. It is reported that the specifications are relatively general as it pertains to systems capabilities. In essence, the specifications recommend basic system/device functionality with desired performance parameters. At this time the specifications are not available since the committee has not approved them. The specification title will be "ARP5533 Specifications for Runway Weather Information Systems" and may have some testing and calibration in the standard.

A listing of all documents that were found during the literature search is in Appendix A—Bibliography.

RWIS Vendors

Two vendors were contacted to solicit their cooperation in developing the testing protocols for their respect pavement sensors. Initially, both manufacturers expressed concerns about state DOTs testing their sensors, but agreed to provide input on developing the procedures.

Both vendors have no issue with using their procedures for calibration of their respective *atmospheric* sensors, One vendor provides the maintenance procedures and calibration requirements for their atmospheric sensors as part of their standard user's guide that is included with every RPU. The calibration procedures for the atmospheric sensors that are used at Sensor A sites are available from the respective sensor manufacturer.

Certified Installer

A major installer and service provider for one vendor's Automated Weather Observing System (AWOS) installations nationwide was contacted. The installer was questioned about certification or calibration of in-pavement sensors. His response was: "We follow [vendor] recommendations, but no field calibration is available now. Our major role is testing and troubleshooting of systems. For in-pavement sensors, that includes cleaning them and testing using water and ice. If they don't work, we replace them."

He was also asked for suggestions on developing an in-pavement sensor testing and field calibration procedure and he responded that developing procedures for testing and calibration is not part of his company's business.

International Organizations

The United States member of the Executive Committee of Standing International Road Weather Commission (SIRWEC) indicated that research performed by SIRWEC members are normally published when papers are presented at their conferences. These papers are published in their preprints and/or on their web site. A review of preprints since their 8th International Road Weather Conference April 1996 found that no research has been conducted on either pavement or subsurface sensors.

A review of the Permanent International Association of Road Congresses (PIARC) Technical Reports found one paper that Dr. Marilyn H. Burtwell of Transport Research Laboratory in England had presented [9]. In her research, she investigated the ability of the sensors to detect the freezing point (or concentration) of 0.5 mm thickness of aqueous rock salt solutions under idealized conditions. Performance was assessed on the accuracy of the freezing point measurement, the repeatability of the measurements and the response to changing salt concentrations and test temperatures.

Experts in the Weather Field

Requests for information were made to experts in the weather field in both the United States and abroad. Letters and e-mails were sent to various experts outlining the objectives of this research project and requesting information.

Responses were received from Mr. Rich Naistat of the NWS in Chanhassen, MN, and Mr. Michael J. Kraus of Forecast Systems Laboratory (FSL) in Boulder, CO. A follow up telephone call was made to Mr. Max Perchanok of Ministry of Transportation in St. Catharines, ON.

Mr. Naistat referred to his NWS's Automated Surface Observing System (ASOS) Technical Manual S100 July 1998 edition [3]. Mr. Kraus indicated that FSL has no formal program that involves field testing or calibration of meteorological sensors. However, they have developed statistical analysis systems to help determine data quality. Mr. Perchanok indicated that his office has conducted some research on pavement sensors and a graduate student has written a paper on the research. He did not remember the title or know where to get a copy. An effort was made to contact Mr. Marilyn Burtwell at Transport Research Laboratory in England. However, it appears that Mr. Burtwell is no longer working at the laboratory.

Telephone contact was made with Dan Eriksson of the Swedish National Road Administration (SNRA). SNRA is very concerned with pavement temperatures. They use a PT-100 sensor to measure pavement temperature. This sensor is basically a thermistor. The SNRA has determined the accuracy of this sensor is ±0.15º C. However, it has been shown that by using different RPUs, the readings from the PT-100 can vary as much as 0.3º C.

Swedish RWIS users have no confidence in freezing point data. Thus, they have not devoted much time testing or calibrating the freezing point parameter. The SNRA has a great desire to have a sensor that reports the surface conditions of pavements. Therefore, much work in research and development is being done to develop a sensor to monitor this parameter.

To monitor the accuracies of their ESS data including the pavement sensors, the Swedish Meteorological and Hydrological Institute reviews the outputs of all the sensors and compares the data against the forecast values.

STAKEHOLDER SURVEY

Overview

The purpose of the survey was to obtain a greater understanding of current user practices concerning ESS (environmental sensor station) equipment. A mail-out survey was conducted of ESS equipment users from various state highway agencies in the fall of 2003. The stakeholder survey assessed the willingness of respondents to implement standard calibration and test procedures and assessed how much they would be willing to invest in using these methods. The survey addressed the calibration of surface pavement temperature, subsurface pavement temperature and subsurface moisture sensors. It also addressed the necessary accuracy and level of complexity that RWIS users are comfortable with when testing and calibrating their RWIS equipment. In addition, users were asked about their use of atmospheric sensors in ESS installations. The survey can be found in Appendix B.

The stakeholder surveys were mailed to an appropriate contact person at each state DOT that was known to be using RWIS. Where Transportation Research Board State Representatives were available, they were also sent a copy of the survey. In total, 68 surveys were mailed to 37 states. Of the 37 states sent a survey, 19 returned a completed or partially completed survey, resulting in a 51 percent response rate

The RWIS stakeholder survey provided valuable insight into the types of sensors used, level of accuracy expected from pavement sensors and the means by which some of them were calibrated. The complete summarized results follow and the complete tabulated results are presented in Appendix C.

Results Summary

Methodology

The survey sought to examine and prioritize needs within the RWIS community. Additionally, questions were written to gain a better understanding of the resources that DOTs are willing to provide to train and conduct more thorough RWIS testing and calibration methods.

The survey document consisted of three sections:

- General Calibration Questions
- Surface Sensor Specific Questions
- Atmospheric Sensor Questions

For tabulation purposes, in the following results, a percentage calculation was performed for each question. This percentage calculation is based on the number of respondents answering the question, not the percentage of the total number of surveys received or sent. Although a respondent may have completed some portion of the survey section, not all questions were necessarily answered. This is particularly evident in the Surface Sensor Specific Questions section. A respondent may have indicated that a given sensor type was in use, but did not answer all of the related questions. For these situations the “No Response” option is used.

Results – Part I: General Calibration Questions

This section assessed the willingness of respondents to implement standard calibration procedures and to invest in implementing the procedures. Of the 19 respondents, 18 answered these questions. The responses to each of the three questions in this section are as follows:

1. If standardized procedures that increase the reliability and usefulness of RWIS sensor data were available, would you be willing to implement them?

   100% Yes   **0%** No

2. If standardized procedures provided consistent, useful results, but required more person-hours to complete, what is the maximum additional time commitment that would be acceptable? Time is expressed in terms of hours to calibrate one RWIS station, which may include multiple sensors.

   22% Less than 1 hour   **11%** 2 to 3 hours
   56% 1 to 2 hours   **11%** 3 to 4 hours

3. If standardized procedures improved sensor usefulness but required additional staff training to implement, what is the maximum investment in additional training that would be acceptable?

   17% Less than 1/2 day   **22%** 1 to 2 days
   39% 1/2 to 1 day   **17%** More than 2 days

Respondents unanimously supported the idea of having standardized calibration procedures available. However, 78 percent said that in order for the procedure to be practical, it would need to require two hours or less per site to complete. Additionally, 78 percent of respondents said that the total training required for calibration procedures would need to require less than two days, with 56 percent indicating that they could only devote one day to training. Only 17 percent responded that they would be willing to commit to more than a total of an additional two days of training for RWIS calibration. This result strongly suggests that the testing procedure must be both easy to learn and simple to carry out in the field to be acceptable to RWIS maintenance personnel.

Few respondents have a procedure in place for sensor calibration, either during installation or on a periodic basis. Of those who do, there is generally little confidence that the procedures are producing the desired level of performance from the sensors. However, depending on sensor type, anywhere from half to three quarters of the respondents replied that they rely on a private contractor to conduct sensor maintenance and calibration rather than undertake those responsibilities themselves. Those states that do monitor the performance of their sensors indicated that they typically compare the data to sensors in similar locations to identify sensors that are not operating properly.

All of the respondents indicated a willingness to implement standardized calibration procedures, provided that they enhance the value of the RWIS. It may be inferred from this response that the survey participants believe that there is additional utility to be had from their RWIS deployments if sensor calibration was improved.

Results – Part II: Pavement Sensor-Specific Questions

In order to equitably compare the sensor types, six pages of the survey addressed the calibration of surface RWIS sensors. The sensor types that were included in the survey were:

- Surface Temperature
- Subsurface Temperature
- Wet/Dry
- Subsurface Moisture
- Salinity
- Freezing Point

The tabulation for each of these types was on the basis of the percentage responding to each question. Table 1 summarizes the responses, including the percentages of respondents indicating that they used a sensor type.

Table 1. Pavement Sensor Survey Results

		Surface Temperature	Subsurface Temperature	Wet/Dry	Subsurface Moisture	Salinity	Freezing Point
Percent of respondents		100%	89%	58%	5%	68%	68%
1. Sensor Manufacturer							
	SSI	89%	94%	82%	0%	92%	63%
	Other	11%	6%	18%	100%	8%	5%
2. Sensor Model							
	FP2000	89%	-	82%	-	92%	63%
	Other	11%	6%	-	100%	-	-
	S16UG-D	-	83%	-	-	-	-
	No Response	-	11%	18%	0%	8%	37%
3. Average Year of first install							
	Year	1996	1994	1996	2001	1996	1997
4. Is this sensor calibrated by:							
	Public Employee	21%	18%	27%	100%	15%	11%
	Private Contractor	74%	76%	73%	0%	69%	42%
5. What is the manufacturer reported or observed accuracy for this sensor?							
	See text						
6. Do you have a specific accuracy requirement for the sensor?							
	Yes	11%	24%	9%	0%	8%	11%
	No	63%	76%	91%	100%	85%	47%
	No response	26%	0%	0%	0%	7%	42%
7a. Do you have a standard procedure to verify accuracy?							
	Yes	26%	12%	36%	0%	23%	16%
	No	68%	82%	64%	100%	69%	42%
	No response	6%	0%	0%	0%	8%	42%
7b. Do you conduct an initial test							
	Yes	26%	6%	18%	0%	15%	5%
	No	21%	24%	45%	100%	31%	37%
	No response	53%	70%	37%	0%	54%	58%
7c. Do you test the sensor periodically?							
	Yes	26%	24%	55%	0%	31%	21%
	No	42%	41%	45%	100%	54%	42%
	No response	32%	35%	0%	0%	15%	37%
8a. Do you have a standard procedure for calibrating this sensor?							
	Yes	37%	12%	73%	0%	38%	26%
	No	53%	82%	27%	100%	54%	37%
	No response	10%	0%	0%	0%	8%	37%
8b. Do you calibrate the sensor periodically?							
	Yes	16%	24%	45%	0%	15%	16%
	No	26%	53%	27%	100%	54%	37%
	No response	58%	23%	28%	0%	31%	47%
9. Do you have a written manual or procedure for calibration,							
	Yes	16%	12%	36%	0%	23%	16%
	No	79%	88%	64%	100%	69%	47%
	No response	5%	0%	0%	0%	8%	37%
10. Are you confident that the procedures used in Question 6							
	Yes	16%	18%	55%	0%	31%	21%
	No	63%	59%	27%	100%	54%	32%
	No response	11%	23%	18%	0%	15%	57%

One question (Question 5) is not represented in the table because the question was not in a yes/no format. The question asked for the manufacturer-reported or observed accuracy for the sensor. The most common response was ± 0.36º F for those that provided an answer for surface temperature sensors. The majority of respondents did not provide a figure. This may, in part, be due to not knowing what the manufacturer specifications are for their pavement sensors. For complete results of Question 5, please see Appendix C.

The survey provided valuable information about the types of sensors used. All of the respondents used surface temperature sensors, indicating that developing a procedure for this sensor type should be a priority. Subsurface temperature sensors were also common, as were salinity/freezing point sensors. Surface moisture sensors were used by roughly half of the respondents. Only one respondent indicated that subsurface moisture sensors were used, suggesting that developing of calibration procedures for this sensor type may have little value at this time.

Of the 19 respondents, all but one indicated that they use SSI's RWIS equipment. One state DOT reported using Vaisala sensors while another state DOT reported using Nu-Metrics sensors along with SSI's equipment. SSI was the most common vendor in all six sensor categories, with a minimum of 63 percent penetration for any given sensor type. Vaisala does not publish the accuracy of their pavement sensor. The majority of states did not report having a specific accuracy or range of values requirements for this parameter.

The average date for a first installation of a sensor type was in the mid- to late-1990s, with some installations dating back as far as 1989-1990. Subsurface moisture sensors are the “newest” of the sensor types, with only one state having installed them in the year 2001. However, this state indicated that their use of the subsurface moisture sensor was to detect frost and not to measure subsurface moisture. Subsurface temperature sensors have the longest period of use, with only three of 18 respondents indicating their first use after the year 2000.

Few respondents indicated that they perform initial or periodic testing of the equipment themselves or that they have established procedures for doing so. Additionally, many of the respondents indicated that they are uncertain if the procedures that either they or a private vendor used were yielding the desired results. Also, a major finding for this research project is that in almost all cases, the sensors are tested and calibrated more often by private contractors than by public employees. While the findings of this research project will not dictate who is to run the procedures, they are designed to give the public organization enough confidence to train their employees and run the procedures without outside aid if they wish.

A number of states indicated that they evaluate the performance of their pavement sensors by observing the values of the outputs and comparing them against adjacent ESS stations. Those states that use private contractors to maintain their equipment make the assumption that the equipment is in calibration.

Results – Part III: Atmospheric Sensor-Specific Questions

Because 95 percent of respondents use atmospheric sensors, there is also a strong need to include those guidelines in a testing and calibration package. The responses to the following questions show that there is more variability in the amount of maintenance that is performed on the atmospheric sensors:

1a. Do you have a standard procedure for calibrating atmospheric sensors you use?

44% Yes
56% No
0% No Response

1b. Do you conduct an initial calibration?

22% Yes
33% No
45% No Response

1c. Do you calibrate the sensor periodically?

61% Yes
11% No
28% No Response

2. Do you have a written procedure or manual for calibration testing and maintenance?

33% Yes
67% No
0% No response

Question 3 requested information about the atmospheric sensor manufacturers. Table 2 shows the breakdown of these sensors.

Table 2. Atmospheric Sensor Survey Results

a. Wind Speed	
RM Young	100%
Others	0%
b. Air	
Thies	100%
Others	0%
c. Humidity	
Thies	100%
Others	0%
d. Precipitation	
WIVIS	33%
Price	33%
OWI	17%
Other/Multiple	8%
e. Visibility	
WIVIS	50%
Belfort	40%
Vaisala	10%
f. Pressure (one response)	
Met One Instruments	100%
g. Radiation (one response)	
Handar	100%

Several questions were also asked about the states' use of atmospheric sensors in RWIS installations. The majority used at least some sort of sensor (95 percent); however only a third had a written procedure for calibration. More respondents indicated that they performed periodic testing than initial tests (61 percent vs. 22 percent).

There was a great deal of commonality in the manufacturers of the sensors, with all respondents using the same wind speed and direction, air temperature, humidity and air temperature sensors. The one state that used a subsurface moisture sensor is also the only state that has implemented the use of pressure and solar radiation sensors. More diversity was seen in the precipitation and visibility sensors, with no one vendor having more than 50 percent penetration. This diversity may be due in part to which parameters are being monitored.

For more complete results about the atmospheric sensor section of the survey, refer to Appendix C.

Conclusion

Because of the strong response from the states, the survey was an excellent tool for learning more about the needs in the RWIS community. The major findings of the survey relate to what type of sensors is most commonly used and the amount of resources DOTs are willing to commit to testing and calibrating sensors. Most DOTs use surface sensors and the most common vendor produces Sensor A. Also, because the time allowed for field testing and calibration is limited, the testing procedures should be designed such that it is easy to train operators and execute in the field.

TEST SELECTION MATRIX

A matrix of various possible field testing procedures was developed for monitoring the measurement of pavement surface temperature, sensor moisture state, and freezing point temperature by pavement sensors parameters. This matrix quantifies the effectiveness of the various field testing procedures so that the most promising methods could be further developed. Statistical methods were used to design the experiment and to analyze the effect of two major factors: sensor type and testing methods. These factors were considered as random independent variables for each sensor parameter. The evaluation matrix was developed to incorporate elements such as testing time required, annualized cost of implementation, annualized cost of training, absolute accuracy and precision. The cost of implementation included labor, materials and equipment used in the installation and testing. Replications in precision and accuracy of each sensor parameter for each experimental cell were used to study interaction between the two major factors.

For this project, the testing and calibration methods for pavement and subsurface sensors are construed as measuring the conformance to or discrepancy from a specification for an instrument. For surface temperature and freezing point values, the proposed testing methods will determine conformance to the manufacturer's recommended specifications. Surface state will be determined under various conditions.

Results of the Experimental Design

Table 3 shows the most effective methods as determined by the experiment.

Table 3. Matrix of Most Effective Methods as Determined by the Experiment

Sensor Parameter	Sensor Type	Testing Method
Pavement Surface Temperature	Ambient Pavement Temperature (Dry & Below 50º F and above freezing)	Contact with Thermistor
	Ambient Pavement Temperature (Wet & Below 50º F and above freezing)	Thermistor, Spray and cover with paper toweling
	Pavement Temperature at 32º F (freezing)	Ice bath with Thermistor
	Pavement Temperature Below 32º F (Dry condition)	Dry Ice with Thermistor
	Ambient Pavement Temperature Below 32º F	Contact with Thermistor
Pavement Condition	Dry Condition	Visual inspection
	Wet Condition	Using a spray
	Freezing Condition	Using a spray
	Frost Condition	Visual inspection
Freezing Point Temperature	Salt Brine (4%, 10%, 15% & 23% concentration)	Spraying solution
Surface State Ice Depth	No sensor identified	No method identified
Subsurface Temperature	No sensor identified	No method identified
Subsurface Moisture	No sensor identified	No method identified

Based on the results of the stakeholder survey, only one state uses subsurface moisture sensors. That state uses its sensor to monitor frost condition, not soil moisture content. RWIS users in this state have no interest in the moisture values that are reported by the sensor. In addition, the testing procedures for subsurface sensors would be difficult to develop, test, and implement as shown in the developed matrix. As a result, it was requested and approved that the resources of the research project be spent on only pavement surface sensors. More information about the Test Selection Matrix can be found in Appendix D.

FEASIBILITY STUDY FOR QUALITY CONTROL OF PAVEMENT SENSOR DATA

To determine the feasibility of analyzing and developing quality control for data from ESS pavement sensors, it is appropriate to first examine the quality control procedures, for meteorological observations, used by other organizations including the National Weather Service (NWS).

The NWS provides a Meteorological Assimilation Data Ingest System (MADIS) that is dedicated to making value-added data available from the National Oceanic and Atmospheric Administration's (NOAA) Forecast Systems Laboratory (FSL). The data is available to improve weather forecasting by providing support for data assimilation and numerical weather prediction. Quality Control (QC) of MADIS observations is important because the retention of erroneous data and/or the rejection of good data can substantially distort forecasts.

Introduction

Observations in the FSL database are stored with a series of flags indicating the quality of the observation from a variety of perspectives, such as, temporal consistency and spatial consistency. Users of MADIS can then inspect the flags and decide whether or not to ingest the observation [14].

Recently, there has been a tremendous expansion in the number of non-National Weather Service automated weather stations and groups of weather stations (commonly referred to as "mesonets") across the United States. Among these systems are the approximately 1,300 ESS sites installed and operated by state departments of transportation. These ESS provide observations of meteorological variables such as pressure, temperature, winds and roadway pavement parameters such as pavement temperature and condition [15]. As of 2004, the NWS collects ESS data from twelve state departments of transportation listed in Table 4.

Table 4. Listing of State Highway Providers by Number of ESS Sites

State Highway Providers Description	Number of ESS Sites	Data Distribution*
Colorado Department of Transportation	107	3
Iowa Department of Transportation	50	2
Kansas Department of Transportation	41	2
Minnesota Department of Transportation	92	3
Utah Department of Transportation	50	3
Montana Department of Transportation	59	3
Wyoming Department of Transportation	23	3
Nevada Department of Transportation	47	3
Washington Department of Transportation	72	3
Idaho Department of Transportation	29	3
Oregon Department of Transportation	27	3
California Department of Transportation	11	3

* The Data Distribution categories are: 1) FSL only – no distribution; 2) Distribution to government, research, and education organizations; 3) Full distribution; 4) Distribution to NWS only.

* Data is as of February 24, 2004 [16]

NWS recognizes these meteorological observations as a cost-effective supplement to their own surface observation network. NWS provided funding to FSL in 1997 to build and implement the Local Data Acquisition and Dissemination (LDAD) system [17] as part of their Advanced Weather Interactive Processing System (AWIPS) installed in each NWS Weather Forecast Office (WFO). LDAD was designed to allow each individual WFO to ingest mesonet observations (in any format), combine the observation from different mesonet data providers and integrate them with other AWIPS datasets by converting the observation to standard AWIPS observation units, time stamp, and formats.

Once integrated into the AWIPS database at each WFO, LDAD also provides for the quality control of the observations, as well as their display on forecaster workstations either as an individual dataset or in combination with other AWIPS datasets.

Combining data from various sources, including public and private, local, and national, has shown an increase in the accuracy of automated quality control (QC) and data monitoring procedures designed to identify individual erroneous observations, as well as longer-term hardware and communication failures. Nonetheless, there are difficulties when combining data from different mesonet sources. These difficulties have long posed a problem for the meteorological community. The characteristics of the mesonets vary considerably from one to another. For example, the number of stations, type of variables reported, observation units, observation time stamps, reporting interval and format of the observation all vary among different mesonets [2].

MADIS Quality Control Approach

The design of the Quality Control (QC) is largely based on requirements specified for incoming data to AWIPS systems running at modernized NWS Weather Forecast Offices. These requirements are, for the most part, provided by the NWS AWIPS Techniques Specification Package [18].

The techniques described in the TSP are meant to: "assure that watches, warnings, and general information disseminated to the public are based on accurate and current data" by:

- Allowing for the selective retrieval of [quality controlled] observation data for use by AWIPS applications programs
- Providing the information necessary to inform personnel responsible for network maintenance about possible malfunctioning equipment so repairs can be made as soon as possible
- Allowing for forecaster correction of clearly incorrect values where a correct value can be obtained

Two types of QC checks are utilized by MADIS meteorological surface dataset, static and dynamic. Static QC checks are single-station, single-time checks which, as such, are unaware of the previous and current meteorological situation described by other observations. Checks falling into this category include: validity, climatological, internal consistency and vertical consistency checks. Although useful for locating extreme outliers in the observational database, the static checks have difficulty with statistically reasonable, but invalid data. To address these difficulties, the TSP also describes dynamic checks that refine the QC information by taking advantage of other available hydrometeorological information. Examples of dynamic QC checks include: positional consistency, temporal consistency, spatial consistency, and model consistency checks [19].

The TSP also describes the requirement for a "data descriptor," a data structure intended to provide an overall opinion of the quality of an observation by combining the information from the various QC checks. Algorithms described to compute the data descriptor are a function of the types of QC checks applied to the observation, the sophistication of those checks and the departure of the observation from the expected values provided by the QC checks.

More information about the details of the QC checks including automated quality control, subjective intervention and QC data structures is included in Appendix E. Short descriptions of these topics follow.

Automated quality control refers to three levels of QC checks. The level 1 checks control for data validity, such as, relative humidity must be from 0 percent to 100 percent. One level two-check controls for temporal consistency, such as, dew point should not vary more than 35º F per hour. The other level 2 check controls for internal consistency, such as comparing the air temperature to the dew point temperature. The level 3 checks control consistency using an Optimal Interpolation (OI) technique. This checks data against neighboring sensors.

Subjective intervention refers to the ability for forecasters to override the QC checks or watch suspect data without labeling the data as bad. QC data structures are the data descriptors that mark data according to whether QC has been applied, the QC levels it passes or fails or its status on a subjective intervention list.

Recommendations for Quality Control of Pavement Sensors

Similar methodology to the previous atmospheric QC could be used to flag pavement sensor data on an ongoing basis. Tables 5 – 9 illustrate potential QC checks for four of the pavement sensor parameters selected in the Matrix For Determining Test Methods. Table 5 is an overview of the QC level that can be performed on the pavement sensor while each of the succeeding tables show possible parameters and reasonable values for each of the levels.

Table 5. Pavement Sensor Parameters with Potential QC

Pavement Sensor Parameter	Max Possible QC Level	Level 1: Validity	Level 2:		Level 3: Spatial Consistency
			Internal Consistency	Temporal Consistency	
Surface Temperature	3	X	X	X	X
Surface Condition	2	X	X		
Freezing Point	2	X	X		
Subsurface Temperature	3	X	X	X	X

*X denotes the QC check should be applied.

Table 6. Potential Level 1 Validity Checks

Surface Temperature	-40º to 130º F
Surface Condition	Dry, Wet, Ice or Frost
Freezing Point	-26º - 32º F
Subsurface Temperature	-10º - 55ºF

Table 7. Potential Level 2 Temporal Consistency Checks

Surface Temperature	35º F/hour
Subsurface Temperature	10º F/hour

Table 8. Potential Level 2 Internal Consistency Checks

Surface Temperature vs. Air Temperature
Surface Temperature vs. Subsurface Temperature
Freezing Point vs. Surface Temperature
Surface Condition vs. Precipitation

Table 9. Potential Level 3 Spatial Checks

Surface Temperature	Compare data to spatially close sensors
Surface Condition	
Freezing Point	
Subsurface Temp.	

These recommendations primarily exist to show possible methods for doing quality control on pavement sensors. The recommendations are based on reasonable values, but have not been researched beyond developing the concept. The development of algorithms for flagging the poor pavement sensor data is outside of the scope of this project.

TESTING METHODOLOGY

Temperature Baseline Methodology and Findings

A variety of temperature baseline data collection approaches were evaluated. Both contact sensors, such as thermistors and thermocouples, and non-contact sensors, such as infrared (IR) thermometers, were included for review. Theoretically, the baseline represents the exact value of the experimental variable. The validation testing balanced a desire for highly-accurate temperature readings with practical considerations, such as field ruggedness, ease of use and cost. Summary tables of the baselines evaluated are shown in Tables 10 and 11. Images of these instruments are also shown in Figures 1-3.

Table 10. Contact-Type Baseline System Components Used in Laboratory and Field Testing

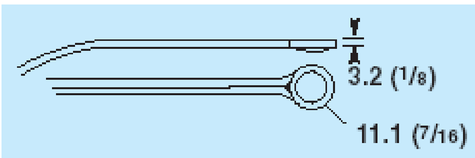
Vendor	Part	Description	Qty.
Omega	ON-409-PP	Precision thermistor	2
Omega	HH41	Precision handheld thermometer	2
Omega	HPS-FSP-T-14E-1E-SLE	Integral handle probe thermocouple	1
Omega	WTT-HD-72-OSTW-M-SLE	Heavy duty washer probe thermocouple	1

Table 11. Non-Contact-Type Baseline System Components Used in Laboratory and Field Testing

Vendor	Part	Description	Qty.
Omega	OS-542	Precision thermistor	1
Omega	OS-951	Precision handheld thermometer	1
Omega	OS-530HR	Handheld digital thermometer	1

Figure 1. Thermistor Baselines Used in Laboratory and Field Tests

Omega HH41 precision handheld thermometer



ON-409-PP precision thermistor

Figure 2. Thermocouple Baselines Used in Laboratory and Field Tests

Omega HH202A handheld digital thermometer

Omega HPS-FSP-T-14E-1E-SLE integral handle probe thermocouple

Omega WTT-HD-72-OSTW-M-SLE heavy duty washer probe thermocouple

Figure 3. Infrared Baselines Used in Laboratory and Field Tests

Omega OS-542 infrared thermometer

Omega OS-951 infrared thermometer

Omega OS-530HR infrared thermometer

Contact Baseline Equipment

Contact baselines were evaluated because they can accurately monitor data throughout the testing period. Generally, contact baselines can provide more accurate readings than other technologies such as infrared thermometers. Two types of contact baselines were evaluated in order to find out which baseline should be recommended for this research project.

Thermistors

Because thermistors served as an excellent baseline in the Aurora Consortium's *Laboratory and Field Studies of Pavement Temperature Sensors*, thermistors were also used for a baseline in this research project. Precision thermistors were temporarily affixed to the pavement using thermal paste. One thermistor was affixed directly to the sensor and the other 2.5 inches from the sensor. Both of the thermistors provided temperature data that was compared to the pavement sensor. The two baselines' positions were used to evaluate which spatial placement more accurately describes the pavement's temperature.

The baseline temperature data was produced from calibrated thermistors capable of measuring temperatures to an accuracy of 0.18° F at 32° F, 0.32° F at –2° F and 0.45° F at –40° F. Ice bath testing was done on these thermistors and the stated accuracy was confirmed. This level of accuracy is generally comparable to or better than the subject sensors' accuracy, making thermistors excellent candidates for use in ESS sensor testing. Detailed thermistor specifications are shown in Table 12.

Table 12. Omega ON409-PP Thermistor Specifications

Temperature Range	**-4º to 212º F**
Accuracy	± 0.18º F
Package	7/16" washer
Leads	10' Vinyl
Connector	Phone Jack
Thermistor Element	44033
Water Resistance	Good
Unit Price	$62

Thermistor sensors have an advantage over technologies such as resistance temperature detectors or thermocouples, because of their accuracy, temperature range, instrumentation availability, package design and cost. Omega was selected as the source for the baseline thermistors to minimize system integration complexities.

For field testing, accuracy, ease of use and robustness are essential. The laboratory testing found limitations to the use of thermistors. One problem was simply keeping the thermistor in place. The lead-in wire was stiff and often prevented the thermistor from staying in place on the pavement. When the thermistor is separated from the pavement or pavement sensor, the physical and thermal contact is lost. Placing a brick that has insulation on its bottom surface on the thermistor lead-in helped to an extent, but it did not eliminate the problem. For field testing, the test protocols were changed and instructed the operator to place the insulated brick directly on the surface of the pavement or pavement sensor. This partially eliminated the effect of the atmosphere at the test location because the thermistor was not exposed to the air. In field testing, this method proved particularly effective in keeping the thermistors affixed to the pavement. This method is recommended in the final test procedures.

One issue that thermistors have is that they need time to acclimate. There is a small metallic mass on the thermistor that requires a few minutes to stabilize. The more the thermistor is handled immediately before use, the longer it takes for the thermistor to stabilize. After stabilization, this acclimation time is beneficial to the test because the thermistor gives very stable readings.

Thermocouples

Thermocouples were also evaluated in the laboratory validation testing to see if they could offer better measurement and usability qualities. For the most part, it was found that the thermocouples were less effective than thermistors for this research project because of physical limitations.

Two different types of thermocouples were evaluated in the validation testing. A wand-type thermocouple was used because it could easily be applied to the sensor and pavement. It was found that this thermocouple was too fragile for field testing. The contact on the tip of the wand was especially fragile and could easily bend when applied to a rough pavement surface.

This thermocouple responded quickly and reported the temperature within a few seconds. This was faster than the thermistor. Besides durability considerations, the greatest problem with this method of measuring temperature was the fact that the user would need to hold the wand on the sensor whenever a reading was needed. In contrast, the thermistors were pre-affixed to the pavement and no extra action was required to take a reading.

Also, the accuracy of the thermocouples was less than the thermistors. The accuracy is only 0.9º F compared to 0.18º F for the thermistors.

A washer-type thermocouple was also considered. It was found that the washer thermocouple would not be suitable for field testing because it must be anchored to the pavement with a concrete screw. Screwing the thermocouple to the pavement would disturb the integrity of the road surface and is therefore not recommended. In addition, adhesion could not be accomplished with thermal paste because the paste would not secure the washer.

Table 13. Thermocouple Probes Specifications

Category	**Specification**	
Manufacturer	Omega Engineering	Omega Engineering
Model	HPS-FSP-T-14E-12-SLE	WTT-HD-72-OSTW-M-SLE
Temperature Range	-328º to 752º F	Not Available
Accuracy	Special	Special
Accuracy	±0.4% of Reading or ± 0.9º F	±0.4% of Reading or ± 0.9º F
Package	Wand Type	washer
Leads	5’	6’
Connector	Stripped end	included
Unit Price	$90 + connector	$29
Lead time	2-3 weeks	2-3 weeks

Non-Contact Baseline Equipment — IR Thermometers

IR thermometers were evaluated as a possible temperature baseline data. IR thermometers have the advantage of remotely capturing temperature data, thereby avoiding contact with the roadway surface. This adds safety to the testing procedure and makes the procedure quicker to run because less setup time is required.

Several different IR thermometers were preliminarily evaluated, and three IR thermometers were purchased for use in the validation testing. These thermometers were chosen because they represent three different types of IR thermometers with varying qualities. The OS-542 is the least expensive and costs $125. Despite its specification of accuracy of only 4º F and fixed emissivity of 0.98 (concrete and asphalt have emissivities of 0.94 and 0.93 respectively), this IR thermometer was chosen to see how well a less expensive model could perform in the validation testing.

The other IR thermometers have better accuracy specifications and adjustable emissivity, but cost much more. The OS-530HR has adjustable emissivity and the OS-951 has automatic emissivity compensation. Complete specifications IR thermometers are shown in Table 14.

The OS-951 also has the advantage that it makes a small sound any time a new reading is taken. This is beneficial because it provides information about the stability of the pavement section. The other IR sensors average past readings after the trigger is pulled while the OS-951 does not. If the OS-951 stops "ticking," the user knows that it has reached a stable temperature. It gives the user more confidence that it has reached a stable and accurate reading.

Generally, all three IR thermometers gave temperature readings within 2-3° F of the thermistor baselines in the laboratory validation testing. A test of the thermometers was run with readings taken once per minute. The average absolute values of the difference between the thermistor baseline and the IR thermometers are shown in Table 14. This table also gives a feel for the variability in temperature accuracy over time. The average absolute values of the differences for the "on sensor" and "2.5 inches away from the sensor" are very close. This showed that IR readings taken on the sensor are just as accurate as those taken on pavement.

Table 14. Average Absolute Value of Difference Between IR Thermometer and Thermistor Reading in Laboratory Tests (ºF)

	On Sensor			2.5" Away from Sensor		
Run Test	**OS-530HR**	**OS-542**	**OS-951**	**OS-530HR**	**OS-542**	**OS-951**
1	0.9	1.9	1	0.6	0.7	1.4
2	0.2	0.8	2.4	0.3	1.6	1.7
3	0.4	1.4	1.5	0.1	0.2	1.9
4	1.7	3.2	0.7	1.6	3.0	1.0
5	1.9	0.8	2.7	3.1	0.8	1.7
6	4.0	0.5	0	2.8	0.3	0.0
7	1.8	1.8	2.8	2.0	1.9	2.7
8	3.0	0.0	0.2	2.7	0.5	0.8
Average	1.7	1.3	1.4	1.6	1.1	1.4

Initially, one method for measuring temperature was to shoot the pavement section with the IR thermometer from the side of the road. A major factor for this method of testing is whether the IR thermometer remains accurate when taken from a warm environment such the cab of a truck to a cold outside ambient temperature. Some preliminary tests were performed to evaluate the sensors. The OS-542 experienced much poorer accuracy when brought in and out of the colder environmental chamber. It required much more time to become accurate while it acclimated to the ambient air temperature. However, the OS-951 experienced far better precision while it acclimated to the ambient temperature. Because this IR thermometer makes contact with the pavement, its readings had less variability. Unfortunately, the use of this thermometer would still require a lane closure. While the other sensors may have been reading the top few air molecules and did not stabilize for minutes, the OS-951 gave more accurate readings immediately. Unfortunately, while the specifications say that the thermometer can take readings down to -22° F, in field tests where the ambient air temperature was below 32° F, the thermometer did not give readings.

Generally, the IR thermometers did not deal with cold temperatures well. In cold temperature laboratory tests, the IR thermometers could not function because of low ambient temperature or low pavement temperatures. One of the laboratory tests was outside of the ambient temperature operating range for all three IR thermometers. In this test, the OS-951 reported a “low ambient” temperature while the others simply gave inaccurate readings compared to thermistors and the environmental chamber’s built-in temperature sensor.

Table 15. IR Thermometer Specifications for Chosen Thermometers

Model	**OS-542**	**OS-951**	**OS-530HR**
Temperature Range	-4º to 932º F	-50º to 550º F	-22º to 250º F
Operating Temperature	32º to 104º F	32º to 122º F	32º to 122º F
Accuracy	± 4º F	± 1% of Reading or ± 3º F	±1% of Reading or ± 3º F
Resolution	0.2º F	0.1º F	0.1º F
Repeatability	±2º F	±0.1º F	Not Given
Display	4 dig LCD	3 dig LCD	3 dig LCD
Emissivity Compensation	Fixed at .98	Auto	Manual
Field of View	12:1	Contact	20:1
Laser Aiming	Dot & Circle	No	Dot & Circle
Distance Measurement	No	No	Optional $75
RS-232 Output	No	Optional $45	No
Unit Price	$125	$299	$345
NIST Calibration	$125	$125	$125

IR thermometers were found to be useful for quick temperature readings and are advantageous due to their lack of setup. However, accuracy limitations prevent this method from being used for the temperature tests.

During the field tests, the infrared thermometers were evaluated and produced results generally within their tolerances for accuracy. Unfortunately, because the temperature tests require greater accuracy than 3-4º F, the results of the infrared readings were not sufficient to recommend. An initial reason for using this type of thermometer was because it would not require a road closure and the operator could operate the device from the side of the road.

Although these thermometers proved to be adequately accurate for indoor use, some preliminary tests on pavement at 3-10 feet away showed that the readings were only accurate to about 10 degrees. These readings were taken from a height of approximately 5 feet and the infrared beam hit pavement at an angle of 30º to the pavement. The inaccuracy of the sensor may be due to the effect of sun radiating off the pavement surface or the reflection of the infrared rays off the pavement. It was also difficult to hold the infrared gun steady enough to get a consistent reading. Distance shots were determined to be not accurate enough to recommend in the Field Test Procedures for Environmental Sensor Stations.

Sensor Stability Definitions

Some of the tests require a stabilization period before a sensor can be determined to pass or fail a test. The following definitions and explanations tell the process that led to the definitions used in the Field Test Procedures for Environmental Sensor Stations.

Sensor Temperature Stability

During many of the testing procedures, the applied thermistors and subject sensors were expected to attain temperature stability. During the laboratory and field tests, the sensor temperature stability was established when four consecutive temperature readings were within 0.4º F (0.2º C) of each other for both the thermistors and subject sensors respectively. This was sufficient and in field tests required about 10 minutes for the thermistors to stabilize.

Additional data was taken in the field to be able to do a further analysis regarding temperature stability of thermistors affixed to pavement or pavement sensors. One method was selected to be included in the Field Test Procedures for Environmental Sensor Stations for determining ambient temperature. This method calls for the operator to affix the thermistors directly to the pavement sensor. Information about why this method was selected can be found in the Ambient Temperature sections of the Findings chapter.

An analysis using Statistical Process Control (SPC) was conducted using the data that was found in the field tests. More information about SPC can be found in the Statistical Process Methodology section of this chapter. Because each run was conducted at a slightly different temperature, the data was normalized by subtracting the thermistor temperature value from the average thermistor temperature value for all the data points for that run. In effect, this process normalized the data so that the control limit (CL) was zero. This data was plotted on a run chart shown in Figure 4. Each of the runs includes the final ten readings taken during that run except one run in Minnesota, which only had eight points.

The standard deviation of all points on the run chart was found to be 0.096° F. This value can be used to find the upper and lower control limits (UCL and LCL), which define the stability criteria. The UCL is 0.288° F and the LCL is -0.288° F. The process is in control when the difference between the points in the run is within a range equal to the difference of these values. This range is 0.576° F which is less strict than the range used in the field tests. Because 0.4° F allowed the temperatures to stabilize in a reasonable amount of time and the recommended procedure in the Field Test Procedures for Environmental Sensor Stations calls for less data points to attain the stability criteria (4 instead of 10), 0.4° F has been selected for the range in which temperatures can fluctuate while still remaining stable according to the test.

Subject Sensor Freezing Point Stability

This stability criteria is only required for testing passive sensors. Because less data was available, the stability criteria for active sensors were found anecdotally. Active sensors must report two readings within 1 degree of each other for the test to be considered stable. These readings are typically taken over an 8-12 minute duration.

For passive sensors, a similar analysis to the one done to determine temperature stability was conducted with the 4 percent freezing point data. For more information about why this concentration was selected, refer to the sections on Freezing Point Tests in this chapter. The data for passive sensors was not as consistent as the temperature errors. Because Sensor A was so accurate in finding freezing point, it had little variability and therefore very small standard deviation when compared to only Sensor A data. This standard deviation was 0.026° F. Sensor B's data varied more and had a standard deviation of all points of 0.764° F. A run chart of the data is shown in Figure 5.

Because Sensor A does not have stability issues because it uses a well (see the findings related to this test for more information), only the Sensor B data was used to determine this stability criteria. Using the SPC control limits, the range was found to be 4.584° F. Again because less data points will be taken, the stability from the field tests (0.4° F) was used in the Field Test Procedures for Environmental Sensor Stations.

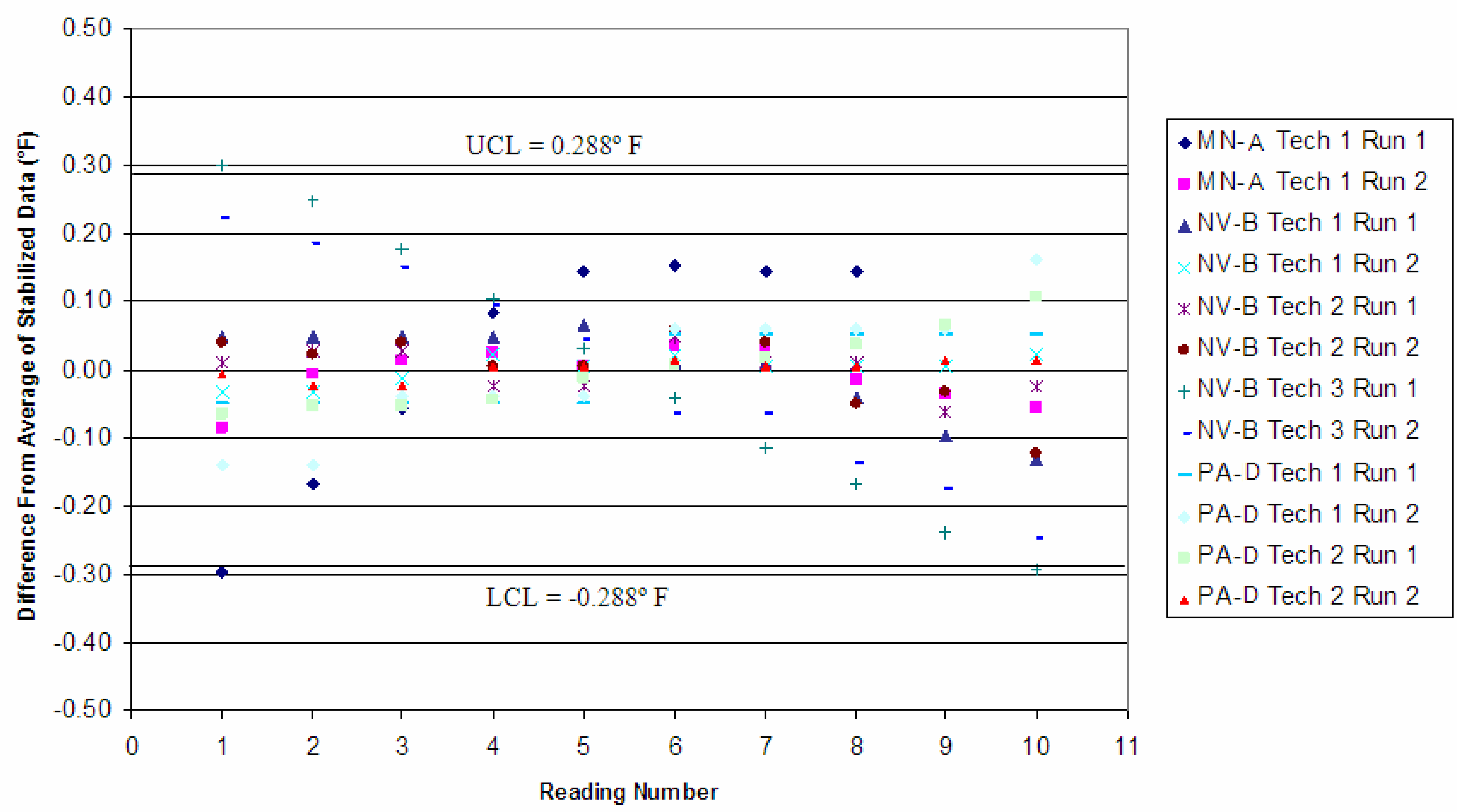


Figure 4. Run Chart for Statistical Process Control of Pavement Temperature for Field Tests

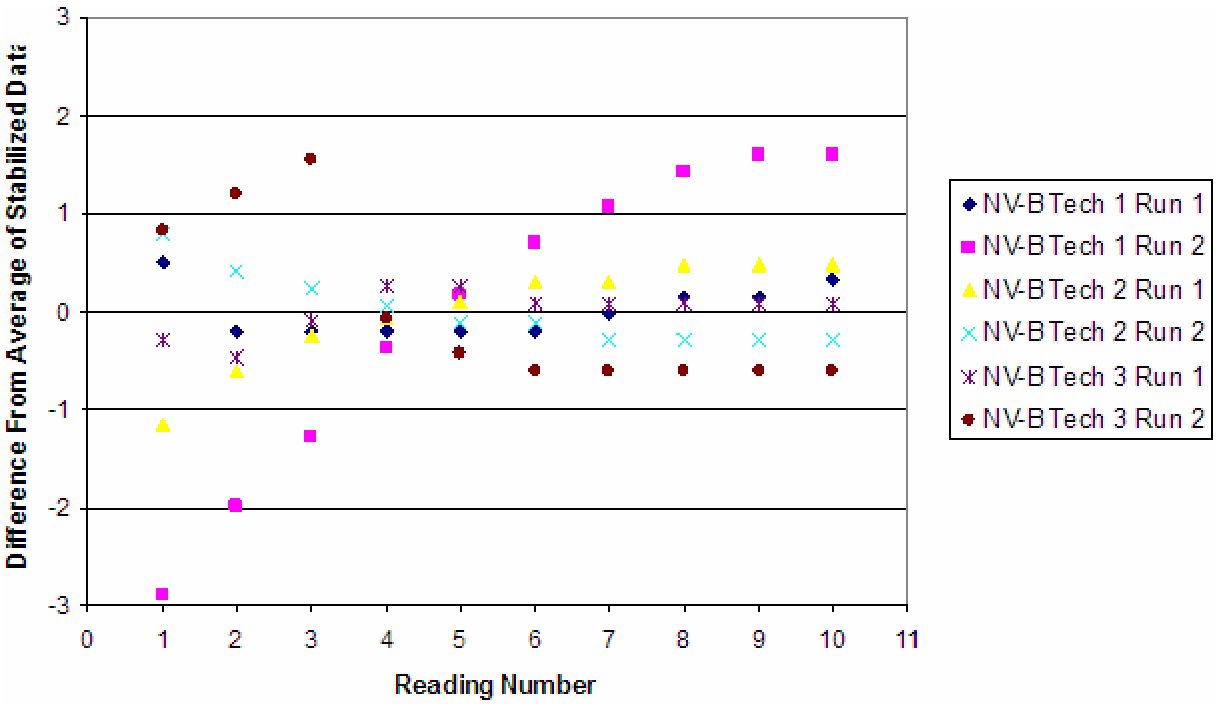


Figure 5. **Run Chart for Statistical Process Control of Freezing Point for Passive Sensors (° F)**

Infrared Temperature Stability

The infrared temperature monitoring unit used in the Validation Test Plan does not require the acclimation time of the baseline thermistors or subject sensor; the temperature is instantaneously obtained. The final reported infrared temperature is the average of three successive temperature readings.

Laboratory Validation Test Methodology

Overview

For each test, subject sensors were tested in a controlled laboratory environment using both asphalt and concrete pavement test sections. Each test was conducted once per sensor and results were compiled and then reviewed by the project team. Following the validation test review, test procedures were modified to improve the tests, and each test was conducted again.

Conducting the validation tests in a laboratory setting provided an opportunity to control for many extraneous variables. For example, the environmental chamber was carefully stabilized before the start of every test, the test equipment was acclimated to the chamber temperature and the ice baths and chemical brines were carefully prepared in a laboratory environment.

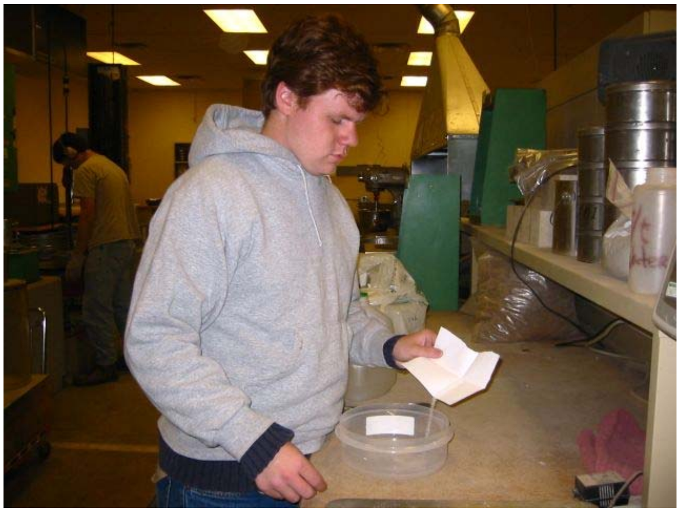


Figure 6. Preparing Sodium Chloride Solutions in the Laboratory

Additionally, the chamber was not exposed to any light for a majority of the tests. Solar radiation was a major factor in the field tests, and the test procedures were run without this extra variable.

A variety of baseline data collection approaches were evaluated. For temperature, both non-contact baseline sensors, such as infrared guns, and contact baseline sensors, such as thermocouples and thermistors, were evaluated for their accuracy and ease of use. Also, the duration of each task including baseline setup, cleaning, procedure steps, sensor stabilization and final clean-up was documented and reviewed to select effective test methods.

Laboratory Environment

Two pavement test sections (one asphalt and one concrete) served as test platforms for evaluating the subject sensors. These test sections are the same sections that were used during the Aurora Consortium's *Laboratory and Field Studies of Pavement Temperature Sensors.*

The concrete test section was made according to Minnesota Department of Transportation Standard Construction Specification Number 2301 and used a type of concrete that is typical for highway construction. 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 sections are approximately 27-inches wide by 60-inches long by 5.5-inches deep. The test section size was selected to accommodate up to seven different subject sensors while being small enough to be maneuverable. Additional space on the test sections was reserved for the addition of new sensors.

Six sensor models were installed in the concrete and asphalt test sections in summer 2003 for the Aurora project. The sensors were installed according to vendor specifications and the procedures recommended in Strategic Highway Research Program report number H-351, *Road Weather Information Systems Volume 2: 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. Photos of the pavement test sections preparation show how the sensors were installed.

Figure 7. Removal of the Asphalt Test Section at Mn/DOT's Mn/ROAD Facility

Figure 8. Concrete Core Drilling in Preparation for Sensor Installation

Figure 9. Concrete Test Section after Sensor Installation

Pavement test sections were placed on wood pallets and metal dollies to facilitate movement in and out of the laboratory test chamber. The pallets and dollies alter the "real world" heat source/sink characteristics of the pavement because the undersides of the test sections are exposed to the pallets, dollies, and open air instead of the ground surface. In the real world, the pavement is in contact with the ground, a significant source/sink of heat. These factors caused the thermal properties of the pavement to differ from a real world environment by an unknown amount, but these differences are inherent limitations of the test.

The Braun Intertec environmental chamber was used to conduct the laboratory portion of the test. This walk-in chamber is seven feet wide by eight feet high by nine feet deep and has a temperature range from -32º C to 32º C (-26.4º F to 90º F). The chamber has a door opening of 35 3/4 inches wide. The chamber is capable of maintaining a stable temperature that varies by approximately 0.5º C (1.0º F). This temperature variability is due to the chamber's cooling cycles. Refer to Figures 4 and 5 for photographs of the test sections inside the chamber.

Figure 10. Concrete Test Section Installed in Environmental Chamber

Figure 11. Asphalt Test Section Installed in Environmental Chamber

Pavement Sensors Tested in Laboratory

The validation of the proposed testing procedures was conducted using the six sensors listed in Table 16. In addition, an active sensor was provided. It arrived already installed in a concrete slab as shown in Figure 12. It should be noted that the sensors are not all be capable of reporting all parameters of the laboratory tests.

Figure 12. Active Sensor Embedded in a Separate Concrete Slab

Table 16. Sensors Used in the Laboratory

In-Pavement Sensors	**Type of Sensor**
Sensor A	Passive
Sensor B	Passive
Sensor C	Passive (Sensor C-P) (asphalt and concrete) Active (Sensor C-A) (concrete only)
Sensor D	Passive
Sensor E	Passive
Sensor F	Passive

The evaluation team for the Aurora project worked closely with participating vendors to evaluate whether the subject sensors were correctly installed and calibrated. Vendors were offered an opportunity to visit the laboratory and field environments during sensor installation and sensor testing.

At the conclusion of the Aurora project, the vendors were invited to participate in this research project. Vendors were told that the NCHRP research project is not an evaluation of their sensor's performance. Instead, their sensors would be used to evaluate different test methodologies for determining proper sensor performance. All of the vendors were willing to participate in the research project, but some had reservations about the level of effort that would be required to support the research project and about the practicality of developing standardized test methodologies.

Data Acquisition System

The intent of this research project is to conduct laboratory and field tests in such a way that the conditions mimic an actual deployment as much as possible. To this end, the manufacturer-supplied sensors and related data collection equipment were used. For example, most subject sensors need an RPU to capture and processes the raw sensor signals. All tests in this research project were conducted with the manufacturer's RPU and any other proprietary data collection devices. This approach has the advantage of paralleling an actual field deployment, but has the drawback of restricting data collection options to what the manufacturer makes available. For example, many RWIS systems use the ESS protocol of the NTCIP standards. NTCIP Object Definitions for ESS Joint NTCIP Committee Standard 1204 requires the current pavement surface temperature be reported in tenths of degrees Celsius. Whenever possible, data output from the manufacturer's system was collected according to the following criteria:

- Baseline temperature data was collected to the nearest 0.01° C.
- Subject temperature data was collected at least to the nearest 0.1° C.
- Data was automatically recorded by the RPU or CPU once every two minutes or less.
- All incoming data included a time stamp.
- Recorded test data was downloaded from the RPU or PC following each test.

Figure 13. Data Acquisition System Outside Environmental Chamber Used in Laboratory Tests

Field Test Methodology

Overview

The field tests were conducted in Minnesota, Nevada and Pennsylvania. The one of the major objectives was to show that the test procedures can be performed in many types of regions. Minnesota represented a plains state; Nevada represented a mountainous state; and Pennsylvania represented a lake effect state. All three of the states primarily use sensor manufacturers, which helped the research project team identify how different sensors react to the procedures in a field environment.

An alternative goal to this selection of states was to encourage political buy-in for the procedures. Because a strong effort was made to design the procedures to be able to be universally applied, it was important to the project team to show that DOTs from across the country can perform the procedures.

All three of these State DOTs were enthusiastic about participating in the research project and learning more about their ESS sensors. Besides the variety of sensors tested, the States also provided a wide variety of technician skill levels in dealing with ESS equipment. The procedures are simple enough that all the technicians could follow them, though the most experienced technicians fared best when capturing the data from the RPU. The Field Test Procedures for Environmental Sensor Stations require that the technician know how to access the data from the RPU, though they may have an aid available, such as a manufacturer's representative. More information about the demographics of the field technicians is presented in the Interview Results in the Laboratory and Field Test Findings section of this chapter.

Training

For each of the state visits, training was conducted the day before the first day of field testing. Training took approximately an hour and a half for classroom training and an extra hour for hands-on training with a break in between.

The first section of training consisted of a MS PowerPoint presentation introducing the project and giving the technicians an overview of the test procedures and the test equipment. The presenter showed the equipment and passed it around the room for the technicians to familiarize themselves with it.

The hands on training proved to be an essential time for the technicians to ask questions and run through the procedures step by step. The presenter read through each of the directions and demonstrated each action that was required for the test procedures. The technicians were asked to follow along with both the procedures and Testing and Maintenance Forms. Through this training, the project team learned how to make the instructions more clear and how to make the maintenance forms easier to use. These revisions have been made to the Field Test Procedures for Environmental Sensor Stations.

Figure 14. Classroom Training During Field Visits

Field Environment

Running the tests in a field environment allowed the project team to see how external variables would affect the test results. Generally, the tests were run smoothly in large part because of the ice fishing shelter that was used to protect the sensors from wind and solar radiation. These are the two greatest factors in limiting temperature variation. Also, the shelter was set up shortly after sunrise that allowed it to shelter a large section of pavement from the sun all day. If the tests had begun later in the day, a more dramatic temperature gradient may have formed as the sun heated the top surface of the pavement.

Figure 15. Ice Fishing Shelter Tent Installed over Pavement Sensor

Figure 16. Cleaning a Pavement Sensor During the Field Surface State Test

Three of the sensors that were tested in the field had previously been tested in the laboratory (Sensor A, Sensor B, Sensor D). Refer to the Laboratory Methodology section for more details about these sensors.

Sensor C tested in Pennsylvania had not been tested in the laboratory and some valuable information about that sensor's configuration was learned while running the field tests. These findings are detailed in the Laboratory and Field Test Findings section of this chapter, but generally relate to the placement of the temperature sensing device on a circuit board suspended in the sensor. It was learned that newer models of Sensor C may be able to read surface temperatures more accurately, but the project team was not able to test these sensors.

Field Data Acquisition Systems

The field data acquisition systems varied from state to state. Because different methods are used to access the data in each place, a different method was used for each sensor. The following descriptions of how each sensor was accessed follows and gives an idea of the flexibility of these communications systems.

Minnesota's Sensor. This sensor is connected to a router which has a serial server which translates the RS-232 commands to TCP/IP. These commands are then transferred over Ethernet to a portable computer. Because the tests are easier to run when the technician can see the sensor data while performing the test, it was necessary to run enough Ethernet cable to get communications out to the pavement sensor. Two 75-foot Ethernet cables were connected in series with a coupler to run the communications to the sensor site. A 100-foot outdoor extension cable was used to get power to the sensor site and a power strip was connected to the extension cord at the sensor site to power the computer and heat gun. At the sensor site, the operator used a telnet application to access the RPU.

Nevada's Sensor. This sensor was accessed using only a serial connection, though again an approximately 100-foot distance was traversed. Because traditional RS-232 communications cannot be done over such a great distance, wireless serial data radios were used as a communications bridge between the RPU mounted on the RWIS tower and the pavement sensor site. Again extension cables were used to get power out to the pavement sensor. At the sensor site, the extension cable powered the portable computer, heat gun and one of the two serial modems. For this method of communication, the commands were sent directly over the computer's COM port using a terminal application.

Pennsylvania's Sensor C. Because the sensor communicates wirelessly to the RPU, the RPU was removed from the roadside cabinet and brought to the sensor site. The RPU was powered off a maintenance vehicle's DC power. Because the pavement sensor was on the inside lane and the cabinet's AC power supply was on the outside lane, it was not possible to get AC power out to the pavement sensor. The vehicle powered the portable computer and RPU. The power inverter was not powerful enough to run the heat gun. Thus, it was found that if AC power is available, it should be used. If not, it is still possible to run all the tests, though it may take longer for the sensors to dry if a heat gun cannot be used. This method of removing the RPU from the cabinet proved to be a flexible way of getting sensor data to the sensor site, but is only available for sensors that communicate wirelessly to the RPU.

Pennsylvania's Sensor D. For this sensor, the original plan was to use the serial data radios as in the Nevada tests, but in the short amount of setup time available on the day before testing, communications could not be accomplished. Instead, the manufacturer's representative stayed at the RPU and told the operator the sensor readings when the operator requested them with a two-way radio. The manufacturer's representative connected to the RPU via RS-232 and accessed the data with a graphical user interface program for accessing and logging the data. This method was successful, but the operators were not able to monitor the changing conditions as well as with the other setups.

STATISTICAL ANALYSIS METHODOLOGY

The statistical analysis methodology in this section presents different ways of analyzing the laboratory and field test data. These methods include descriptive statistics, scatter plots, regression analyses, and repeatability and reproducibility of the data for accuracy and precision evaluations. One-way and two-way analysis of variance (ANOVA) is used in repeatability and reproducibility analysis. Different tests of hypothesis have been used to analyze test readings from one point or test to the next as a measurement of sensor bias or gain.

The following definitions are provided to clarify the terminology used in the statistical analysis:

- **Resolution** is the ability of the measurement system to detect and faithfully indicate small changes in the characteristic of the measurement result. Resolution is defined as the number of significant digits of the output from the installed sensor and data logger system, e.g., 0.1, 0.01, 0.001. The resolution of the sensor will be a part of the resolution of the total system.

- **Bias** is a quantitative term describing the difference between the average of measurements made on the same object and its true value.

- **Precision** refers to how closely multiple measurements of the same quantity cluster to one another. The precision can be statistically defined by the variance of a group of readings. The bigger the variance is, the less precise the readings and vice versa.

- **Accuracy** is a qualitative term referring to whether there is agreement between a measurement made on an object and its true (target or reference) value. Accuracy is defined as the variance of the output of the sensor and data logger system from the reference value. The accuracy of a reading can be determined to be within some limit of error. The accuracy of the sensor will be a part of the accuracy of the system.

Accuracy measures the difference between the sensor reading and baseline data. Accuracy can be analyzed with the following statistical methods:

- **Mean Difference** is the average difference of all sensor readings. This value is useful in identifying the general trend in sensor performance, but it can hide sensor errors if some sensor readings are high and some are low, resulting in little net difference overall.

- **Mean Absolute Difference** is the average difference of the absolute values of each sensor reading. This value does not allow high and low values to cancel each other because the absolute value of each difference is measured.

- **Root Mean Square Difference** also does not allow high and low values to cancel each other. This measure is more sensitive to data points that are further from the mean. For example, a sensor that provides 5 out of 5 readings that are 1 degree different will have a lower root mean square than a sensor that has 4 accurate readings and a fifth reading that is five degrees different.

Because the accuracy of the sensors is so important, data point outliers were identified and eliminated using a t-test. The basic statistics used in a t-test are sample mean and standard deviation. The form of the test statistic is based on the standard deviation and is estimated from the data at hand.

The t-test statistic is:

$$t = \frac{\overline{Y} - Y_0}{s / \sqrt{N}}$$

For a test at given significance level, such as, 0.05, the hypothesis associated with each case enumerated above is rejected if:

$$|t| \geq t_{\frac{\alpha}{2};N-1}$$

$$t \geq t_{\alpha;N-1}$$

$$t \leq -t_{\alpha;N-1}$$

Where $t_{\alpha/2;\,N-1}$ is the upper $\alpha/2$ critical value from the *t* distribution with *N-1* degrees of freedom and similarly for cases (2) and (3). Critical values can be found in a t-table.

Repeatability measures the changes in accuracy over time. Repeatability includes an assessment of sensor drift (bias) and gain in performance, such as when a sensor is in need of calibration. All sensors will be calibrated before the start of a test cycle. The amount of calibration required will provide a measure of the sensor's drift over time. Bias and gain over time will be evaluated as part of the bench test procedures. Repeatability is the variability of the measurements obtained by one person while measuring the same item repeatedly. This is also known as the inherent precision of the measurement equipment. Knowing the repeatability helps you identify any major problems with the measurement system before you add other possible sources of variability.

It is a standard practice to quantify the measurement capability of an instrument by using a precision-to-tolerance ratio, (P/T). In this ratio, P represents 5.15 times the total measurement error, and T represents a tolerance specified by the agency.

$$\frac{P}{T} = \frac{5.15\frac{S}{c_4}}{\Delta} \qquad \text{Equation 1}$$

Where, S represents the average of the standard deviations and c_4 equals 0.9213 and 0.9727 for four and ten measurements per run, respectively. The value of $\Delta = USL - LSL$ represents the difference between the upper and lower specification limits. When you achieve a

P/T ratio of <0.1, the instrument will make acceptable measurements. When the ratio lies between >0.1 and <0.3, the instrument will make marginal measurements. And if the ratio exceeds 0.3 then the measurements are unacceptable. Since the error tolerance is determined Equation 1 is rewritten by assuming 0.3 of P/T.

$$\Delta = 17.17 \frac{S}{c_4} \qquad \text{Equation 2}$$

Specifically, repeatability test was conducted by having an operator make multiple measurements of the pavement surface temperatures. In a typical test, one operator takes four or ten readings without changing the setup. Equation 2 was computed and Δ was found for each operator and each method.

Reproducibility is the variability of the measurement system caused by differences in operator behavior. Mathematically, it is the variability of the average values obtained by several operators while measuring the same item.

The ANOVA table is useful in determining which sources of variability are significant statistically. In general, if the significance value is less than 0.05, than the source of variability is significant. Standard practice is to use a significance level of 5% as the decision point, with anything above 5% not considered significant.

The analysis of variance method (ANOVA) is the most accurate method for quantifying repeatability and reproducibility. In addition, the ANOVA method allows the variability of the interaction between the appraisers and the parts to be determined.

The ANOVA method for measurement assurance is the same statistical technique used to analyze the effects of different factors in designed experiments. The ANOVA design used is a two-way, fixed effects model with replications. The ANOVA table is shown in Table 17.

Table 17. Two-Way ANOVA Table

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Statistic
Appraiser	SSA	a-1	$MSA = \frac{SSA}{a-1}$	$F = \frac{MSA}{MSE}$
Parts	SSB	b-1	$MSB = \frac{SSB}{b-1}$	$F = \frac{MSB}{MSE}$
Interaction (Appraiser, Parts)	SSAB	(a-1)(b-1)	$MSAB = \frac{SSAB}{(a-1)(b-1)}$	$F = \frac{MSAB}{MSE}$
Gage (Error)	SSE	ab(n-1)	$MSE = \frac{SSE}{ab(n-1)}$	
Total	TSS	N-1		

$$SSA = \sum_{i=1}^{a} \frac{(Y_{i..})^2}{bn} - \frac{Y_{\bullet\bullet}^2}{N} \qquad \text{Equation 3}$$

$$SSB = \sum_{j=1}^{b} \frac{(Y_{.j.})^2}{an} - \frac{Y_{\bullet\bullet}^2}{N} \qquad \text{Equation 4}$$

$$SSAB = \sum_{i=1}^{a}\sum_{j=1}^{b} \frac{(Y_{ij.})^2}{n} - \frac{Y_{\bullet\bullet}^2}{N} - SSA - SSB \qquad \text{Equation 5}$$

$$TSS = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{n} Y_{ijk}^2 - \frac{Y_{\bullet\bullet}^2}{N} \qquad \text{Equation 6}$$

$$SSE = TSS - SSA - SSB - SSAB \qquad \text{Equation 7}$$

a = number of operators,
b = number runs,
n = the number of readings, and
N = total number of readings (abn)

The measurement system repeatability is

$$\text{Repeatability} = 5.15\sqrt{MSE} \qquad \text{Equation 8}$$

The measurement system reproducibility is

$$\text{Reproducibility} = 5.15\sqrt{\frac{MSA - MSAB}{bn}} \qquad \text{Equation 9}$$

The interaction between the appraisers and the parts is

$$\text{I} = 5.15\sqrt{\frac{MSAB - MSE}{n}} \qquad \text{Equation 10}$$

The measurement system repeatability and repeatability is

$$R\&R = \sqrt{\text{Repeatability}^2 + \text{Reproducibility}^2 + I^2} \qquad \text{Equation 11}$$

The total error tolerance is determined by replacing S in Equation 2 with *R&R* in Equation 11 and reflects both the repeatability and reproducibility components of error in the measurement process, including the significant interaction component of error.

Response Time is the time that is required by the selected sensor to measure and report a known value change such as pavement temperature change or change in chemical solution composition.

A one-way ANOVA layout is used when there is a single factor with several levels and multiple observations at each level. With this kind of layout the mean of the observations can be calculated within each level of the factor. The residuals will tell the variation within each level. It is also possible to average the means of each level to obtain a grand mean. Deviation of the mean of each level from the grand mean helps explain the level effects. Finally, variation within levels can be compared to the variation across levels, giving an "analysis of variance."

It can be shown that given the assumptions about the data stated below, the ratio of the level mean square and the residual mean square follows an F distribution with degrees of freedom as shown in Table 17, the ANOVA table. If the F-value is significant at a given level of confidence (greater than the cut-off value in an F-Table), then there is a level effect present in the data.

When there are two factors with at least two levels and one or more observations at each level, one can use a two-way ANOVA layout. Two-way layouts cross every level of Factor A with every level of Factor B. With this kind of layout it is possible to estimate the effect of each factor (main effects) as well as any interaction between the factors.

Like testing in the one-way ANOVA, two main effects are tested and the interactions are zero. Again a ratio of each main effect, mean square and the interaction mean square are formed to get to the residual mean square. If the assumptions stated below are true then those ratios follow an F-distribution and the test is performed by comparing the F-ratios to values in an F-table with the appropriate degrees of freedom and confidence level.

Linear least squares regression can be used to estimate unknown parameters are computed. In the least squares method the unknown parameters are estimated by minimizing the sum of the squared deviations between the data and the model. The minimization process reduces the over-determined system of equations formed by the data to a sensible system when the number of parameters in the functional part of the model equations is unknown. This new system of equations is then solved to obtain the parameter estimates.

A simple quadratic curve is linear in the statistical sense and used in the data analysis.

$$f(x;\beta\vec{\beta}) = \beta_0 + \beta_1 x + \beta_{11} x^2$$

Stability is determined by using a control chart. The control chart is a statistical tool used to distinguish between process variation resulting from common causes and variation resulting from special causes. Repeated measurements are obtained using a measurement device on the same unit (frequently called a master) to measure a single characteristic over time. As measurements are taken, points within the limits indicate that the process has not changed. A stable process is one that is consistent over time with respect to the center and the spread of the data. Stable processes are those that are free from special cause variation.

The upper control limit (UCL) and lower control limit (LCL) are calculated as follows such that we have an indication that a change in data is significant.

$$UCL = CL + 3\sigma$$

$$LCL = CL - 3\sigma$$

*Where CL is a target measurement.

The appropriate time interval is often a major consideration when analyzing the measurement system. Knowledge of the circumstances and conditions in which the equipment is used will help identify special causes when the system is unstable. Action should be taken to make the measurement system robust to the conditions that cause instability. The more likely it is that the measurement system will change, the shorter the interval should be between measurements.

LABORATORY AND FIELD TEST FINDINGS

This section interprets test results from the laboratory validation tests and the field tests. Interpretations from the results of the temperature, surface state and freezing point tests follow. They are presented with a brief overview of the tests and follow the development of the test procedures. To keep the graphs and tables neat, a code has been assigned to each sensor in the test findings. Table 18 shows the seven tested pavement sensors, locations tested, and a code used in the graphs and tables.

Table 18. Designation Codes for Sensors Tested in Field and Laboratory Tests

Sensor Designation	Location Tested	State	Code
Sensor A	Lab and Field	Minnesota	MN-A
Sensor B	Lab and Field	Nevada	NV-B
Sensor C	Lab and Field	Pennsylvania	PA-C
Sensor D	Lab and Field	Pennsylvania	PA-D
Sensor E	Lab Only	Not Applicable	
Sensor F	Lab Only	Not Applicable	
Sensor G	Lab Only	Not Applicable	

The data for all tests is included in Appendices G and J. Because the field tests were limited by time, all of that data is presented in Appendix J. The laboratory data presented in Appendix G was chosen to demonstrate particular findings. These findings are explained in the text below.

No significant differences were found regarding the asphalt and concrete in the laboratory tests. Because test procedures focus on the pavement sensors, there is little opportunity for the pavement type to play a major role. Material properties are most likely affect temperature tests and some of the possible issues are explained in that section.

Temperature Tests

This section explains all tests in which the pavement surface temperature was evaluated. In order to identify the best test methods, many different conditions and temperatures were tested in the laboratory. Out of those tests, three were included in the Field Test Plan and were tested in the three different states. The tests are: Pavement Temperature at Ambient Conditions, Ice Bath at 32º F and Pavement Temperature Forced Below Freezing. The final Field Test Plan used in the state visits can be found in Appendix H.

The goal of using a variety of types of tests was to be able to test different temperature conditions. The first test could be run at any temperature, although typical conditions would usually be above 32º F. The second test forced the pavement sensor to exactly 32º F. The last test measured sensor responsiveness to extreme cold conditions when a block of dry ice was applied to the sensor

Ambient Temperature Tests

Depending on climate, season and daily weather conditions, ambient temperature conditions can vary widely. This could pose problems for procedures that force the pavement to a specific temperature. Thus, this test may be run at any ambient condition. It compares baseline temperature to the temperature reported by the RPU.

The selection of baselines is especially critical for the ambient temperature tests because accuracy is paramount. All the baseline methods and instruments described in the Baseline Methodology section were tested in the laboratory environmental chamber. Physical and functional properties of each baseline are also discussed in that section. In order to preserve the temperature in the chamber while running the tests, infrared readings were taken immediately after the stable thermistor readings had been recorded. The thermocouples were tested in a similar manner, though one thermocouple was not suited for this test and the other thermocouple was not rugged enough to be thoroughly tested. As explained in the Baseline Methodology section, a decision not to test thermocouples was made early in the laboratory validation testing process.

One major consideration for the laboratory tests was that the pavement slabs required time to stabilize in the environmental chamber. During the laboratory tests, the chamber required days to stabilize the pavement sections to the required temperature before the test. This ensured the temperature of the pavement sections would be stable and that temperature variation would be limited to the limitations of the testing procedure and internal conditions within the chamber, such as air flow within the chamber. Even after the pavement sections had been stabilized over a long period of time, a new stabilization problem emerged.

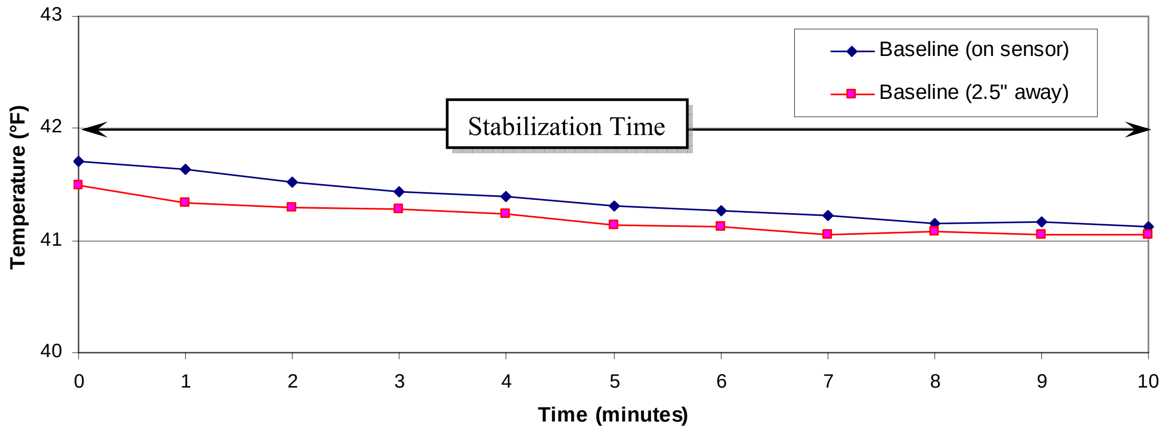


Figure 17. Graph of Time to Stabilize Pavement after Closing Environmental Chamber Door, Baseline Comparison

While the operator affixed the thermistors to the pavement, heat from the operator's hand was transferred to the thermistor. It required about ten minutes for the thermistor to completely stabilize after being handled. This is shown in Figure 17, which is a graph of time and temperature for the two baselines for one of the ambient temperature tests. Note that the thermal energy from the thermistor was not significant enough to affect the much larger pavement sensor. A note has been added to the Field Test Procedures for Environmental Sensor Stations so that the operator knows to touch the thermistor as little as possible to reduce the thermistor stabilization time.

Tests in the field exhibited a similar phenomenon, showing that this temperature stabilization time is an inherent limitation to using thermistors in this manner. Some time could be eliminated from the test by wearing insulated gloves so that the thermistor remains close to the ambient temperature. However, it is important for the operator to be dexterous enough to set up the thermistors so that they make good thermal contact with the pavement.

The following analysis compares the different baseline instruments and evaluates the ambient temperature tests.

Laboratory Ambient Temperature Tests. In order to determine the best temperature measurement conditions, a variety of temperature and wet/dry conditions were analyzed.

Two tests were conducted at 40º F. One was run with a dry condition and one was run with a wet condition. Both tests required the operator to clean the sensor surface before the test and apply the baselines to the sensor surface using thermal paste. For the wet test, a 0.5 mm film of water was added to the surface of the sensor. The results of the two tests were very similar, though the water's heat capacity softened the temperature fluctuations of the baselines and sensors. The water insulated the thermistors against the rapid changes in air temperature due both to the cooling fans turning off and on and the turbulent pattern of air currents in the cooling chamber.

One problem with the wet version of this test is that the bottle that contains the water for the film must stabilize to the chamber and pavement section temperature. For the field tests, this would require the bottle to stabilize to the temperature of the ambient conditions at the sensor site. Otherwise, the water will have the added effect of warming or cooling the pavement and thermistor. The effect of this is shown in Figure 18. The thermistor baseline on the sensor closely followed the sensor reading because the water was applied only to the area on the surface of the sensor while the baseline that was 2 1/2 inches away remained dry and experienced a steadier temperature while the other sensor was stabilizing.

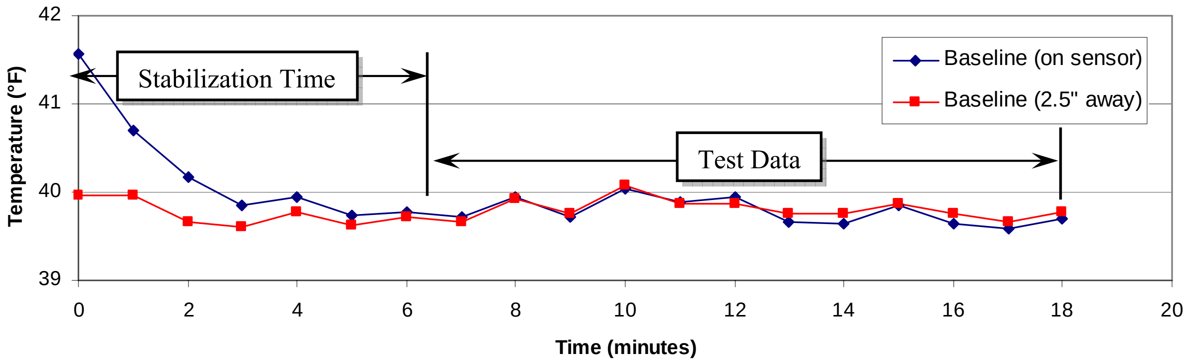


Figure 18. Graph Showing Effect of Water Film Cooling on the Pavement Section in Laboratory Test

Also, two different sizes of bottles were evaluated in the laboratory. These bottles are shown in Figure 19. If the smaller bottle is held in the operator's bare hand, heat may transfer from the hand to the water bottle and change the surface temperature when the water is sprayed. From a practicality and availability standpoint, the larger bottle was chosen for the field tests.

Figure 19. Two Types of Misting Bottles Evaluated in the Laboratory Tests

Both of these temperature tests were run to determine whether a film of water had an effect on the temperature sensors. It was found that the extra step of adding the water film does not significantly affect the accuracy of the test results. While the water film does soften the fluctuations of the thermistor baseline, it adds another variable to the field testing procedure. It was recommended that only the dry test procedure be included in the field tests. That said, the two tests showed such similar results that test could be run on pavement that is wet as long as extra attention is given to drying the spots where thermal paste will be applied to make good thermal contact.

In addition to this wet/dry comparison at 40º F, an additional dry comparison was conducted to compare test methods at another temperature. The same test procedures were also used to test at 20º F. A wet test at this temperature would have formed ice and made the procedure more difficult to run. Similar results were obtained, though the colder temperature required more time for the environmental chamber to stabilize the pavement sections. Because the ambient temperature outside the environmental chamber was close to 75º F, the fans inside the chamber needed more time to stabilize to 20º F. Upon stabilization, the findings from this test were comparable to the tests done at 40º F.

Because temperature accuracy around water's freezing point is important, most of the tests were conducted near that temperature. However, there is no reason to believe that accuracy would be diminished at higher temperatures. Therefore, this test is very flexible and can be run under many different surface state and temperature conditions as long as the thermistors can make good contact with the pavement.

Field Ambient Temperature Tests. The results of the ambient temperature field tests were similarly accurate to those found in the laboratory and during the *Laboratory and Field Studies of Pavement Temperature Sensors* done for the Aurora Consortium. Because the field test procedures retained the two position baselines from the field tests, it was possible to compare the temperatures on and off the pavement sensor. Additionally, the infrared baselines were also tested.

The goal of the ambient temperature field test is to measure how well the pavement sensor can read the pavement temperature. Two spatial methods and three baseline instruments were used in the field tests. The first spatial method took readings directly on the pavement sensor in a uniform area of the sensor, while the other took readings 2 1/2 inches from the edge of the sensor. In field testing, no spatial method was found to be significantly better. The three baseline instruments that were evaluated were the thermistor and the two infrared thermometers.

The ambient temperature field tests were run on all the field sensors that were tested. This test was generally run as early in the day as possible so that the pavement temperature did not have a chance to change temperature due to solar radiation. For this test, it is desirable for the pavement to have as uniform a temperature as possible. The use of an ice fishing shelter provided a good way to keep solar radiation off the sensor.

Table 19 summarizes the performance of the six different test methods with respect to temperature precision and accuracy for each pavement sensor. Precision is the statistical variance of a set of readings. The accuracy of the test methods is the average absolute mean difference between the pavement sensor and each of the baseline methods.

Table 19. Precision and Accuracy of Testing Methods for Field Tests

Test Method	Precision				Accuracy			
	MN-A	NV-B	PA-C	PA-D	MN-A	NV-B	PA-C	PA-D
Thermistor on sensor	0.22	0.09	0.06	0.22	0.36	1.32	0.58	5.45
Thermistor 2.5" from sensor	0.09	0.11	0.05	0.05	1.21	0.49	0.74	2.1
OS-951 IR Thermometer On sensor	0.82	0.41	0.32	0.49	1.85	3	1.72	3.43
OS-951 IR Thermometer 2.5" from sensor	0.66	0.44	0.3	0.46	2.89	3.54	1.87	1.42
OS-530HR Thermometer On sensor	N/A	0.23	0.16	0.17	N/A	2.77	2.02	8.12
OS-530HR Thermometer 2.5" from sensor	N/A	0.24	0.15	0.16	N/A	2.27	1.87	4.82

*Values for precision are derived from the standard deviation of all the points in the sample set.
*Accuracy is derived from the absolute average temperature difference between the thermistor and pavement sensor.

Before the precision and accuracy of the test methods were estimated, a t-test was used to identify the outliers in one run of Minnesota data. The outliers were tested against the rest of data to see if they belong to the group in the run. If the suspected outliers were found to not belong to the run, they were removed.

Each of the precision and accuracy results was converted to a rating based on the normalized selection factors developed in the matrix discussed earlier. The ratings are on a scale of 1 to 10 with 10 being the highest score. The performance factors are shown in Table 20. The thermistor baselines had similar accuracy rating and precision ratings. Because it is important to compare the pavement surrounding the sensor to the sensor reading, the thermistor 2 1/2 inches away from the sensor is used as the main baseline for the Field Test Procedures for Environmental Sensor Stations. The procedures recommend the use of a thermistor on the sensor to better understand temperature inconsistencies while running the test.

While the infrared thermometers had generally good precision, their accuracy was significantly worse than the thermistors. The accuracy obtained by using the thermistors outweighed the minimal amount of setup and stabilization time required for them.

In order to determine the accuracy requirement for the Field Test Procedures for Environmental Sensor Stations, the Nevada data was analyzed because it had the highest thermistor/pavement sensor difference for all the sensors except Pennsylvania's Sensor C which was excluded because of its lack of resolution and different physical configuration.

Because absolute error was used to analyze errors in one direction while deviations in the other direction were ignored, it is appropriate to use a one-tailed method to establish the confidence limits. Using a sample size of four readings for the four stable points required in the Field Test Procedures for Environmental Sensor Stations, the required accuracy for 95% confidence is 1.9° F (1.1° C). For practicality, this number was rounded to 2.0° F (1.1° C). Calculations are provided in Appendix K.

Table 20. Performance Factors of Test Methods (°F)

Test Method	Precision				Accuracy			
	MN-A	NV-B	PA-D	All	MN-A	NV-B	PA-D	All
Thermistor on sensor	7	7	8	7.3	8	4	6	6.0
Thermistor 2.5" from sensor	7	7	9	7.7	4	7	4	5.0
OS-951 IR Thermometer On sensor	5	6	6	5.7	3	2	3	2.7
OS-951 IR Thermometer 2.5" from sensor	5	6	6	5.7	3	2	3	2.7
OS-530HR Thermometer On sensor	NA	7	7	7.0	NA	3	3	3.0
OS-530HR Thermometer 2.5" from sensor	NA	7	7	7.0	NA	3	3	3.0

Table 21 shows the resolution of each of the sensors tested in the field tests. This becomes important when comparing the repeatability of a method. Because repeatability is based on standard deviations of each data set, a lower resolution will give a more precise standard deviation. The resolution of the Sensor C tested in Pennsylvania was used to determine the normalized selection factor in precision. The accuracy of the sensors is the absolute mean difference between pavement sensors and reference (thermistor located 2 1/2 inches from the sensor).

Table 21. Pavement Sensor Temperature Resolution (ºF)

Sensor	Resolution
MN-A	0.010
NV-B	0.018
PA-C	0.100
PA-D	1.000

The field ambient temperature testing was very thoroughly conducted to have a good idea about the repeatability and reproducibility of the tests. For each run, after the temperatures had reached the stability criteria of not varying by more than 0.4° F (0.2° C), an additional 10 readings were taken over the next 20 minutes. Although this added time to the tests, the information was valuable for analysis. Because the additional readings were taken after stability had been attained, a Statistical Process Control (SPC) could be done with the analysis. This type of analysis is appropriate to determine when the dependent variable, temperature in this case, should theoretically be stable.

The repeatability and reproducibility analysis was performed for each test method for each sensor type. Due to the environmental changes during the test, the absolute difference between the pavement sensor and baseline was analyzed for each case instead of directly comparing temperature measurements. The repeatability analysis was performed first for each operator with at least two runs. In the analysis, the average standard deviation was corrected based on the number of data in each run.

Since the upper and lower specification limits were not available, the difference between the limits, called the error tolerance, was determined by assuming a precision-to-tolerance ratio of 0.3. The error tolerances for repeatability are shown in Table 22. The assumed precision-to-tolerance ratio represents the minimum attainable precision-to-tolerance ratio because the analysis includes no other source of variation, such as the variation due to different operators.

Table 22. Error Tolerances for Repeatability for Field Tests (°F)

Test Method	MN-A		NV-B		PA-D		PA-C		
	Operator 1	Operator 2	Operator 1	Operator 2	Operator 3	Operator 1	Operator 2	Operator 1	Operator 2
Thermistor on sensor	1.05	1.51	1.05	1.72	2.07	1.05	0.53	2.54	5.27
Thermistor 2.5" from sensor	0.80	2.20	1.07	1.28	1.91	1.23	0.69	0.98	0.63
OS-951 IR Thermometer On sensor	10.25	9.09	11.58	7.02	3.66	6.77	4.22	11.01	6.26
OS-951 IR Thermometer 2.5" from sensor	4.90	10.26	6.28	13.77	4.23	7.75	3.27	7.64	8.18
OS-530HR IR Thermometer On sensor	NA	NA	2.90	2.58	2.63	2.21	2.27	3.28	2.54
OS-530HR IR Thermometer 2.5" from sensor	NA	NA	2.77	4.00	2.18	1.51	2.30	3.39	2.32

The four test methods that used the thermistor and the OS-530HR IR thermometer showed reasonable repeatability while the test methods with the OS-951 IR thermometer showed variability and less repeatability. If a tolerance is specified within 3° F, the test methods with the

OS-951 IR thermometer are not repeatable. If an agency has a specification for acceptable tolerance, it can be compared to the tolerance for repeatability to get a sense of which baselines give acceptable repeatability.

The repeatability and reproducibility analysis was performed to look into the variation due to operators or human errors and due to the interaction between operators and runs. Two-way ANOVA with replicates was used in a spreadsheet format, resulting in a total measurement error. The same precision-to-tolerance ratio of 0.3 was assumed for the determining the error tolerance to ensure repeatability and reproducibility, as shown in Table 23. The Sensor C data was not included in this table, because its error tolerances were universally very high as the sensor has a one degree resolution which is much greater than most pavement sensors installed in the United States. Any variation in the error tolerances for this sensor is just as likely due to random variation. A calibration factor was applied to the error tolerance of thermistor and IR thermometer measurements on NV-V sensor in Table 23. However, the application of calibration factors to all the test methods on PA-N reduced their error tolerance by about 50 percent, which were still relatively large. The error tolerances are therefore not presented in Table 23.

Table 23. Error Tolerances for Repeatability and Reproducibility for Field Tests (ºF)

Test Method	**Sensor Type**			
	MN-A	**NV-B**	**PA-D**	**All**
Thermistor on sensor	1.27	4.45	1.24	2.32
Thermistor 2.5" from sensor	5.31	3.03	1.59	3.31
OS-951 IR Thermometer On sensor	20.31	28.11	26.22	24.88
OS-951 IR Thermometer 2.5" from sensor	21.15	41.92	23.73	28.93
OS-530HR IR Thermometer On sensor	NA	4.78	5.4	5.09
OS-530HR IR Thermometer 2.5" from sensor	NA	3.97	5.81	4.89

Four test methods with thermistors and IR thermometers showed reasonable repeatability and reproducibility while the test methods with IR showed variability and less repeatability and reproducibility, indicating the need for improvement or calibration. The performance factors can be determined from Table 23 if the normalized selection factors have been established for repeatability and reproducibility.

Ice Bath Tests

Laboratory Ice Bath Tests. Two laboratory tests used ice baths to establish known temperatures. One test was run with a distilled water bath while the other was a sodium chloride brine bath. For initial tests, a section of 12-inch diameter PVC pipe was secured to the pavement surface with silicone to make a watertight seal around the pavement the sensor. Water or brine was then poured into the pipe section and ice was added to lower the water or solution's temperature. Images of this process are shown in Figures 20 and 21.

Figure 20. Laboratory Method for Establishing Ice Bath - Caulk PVC Pipe to Pavement Surface with Silicone

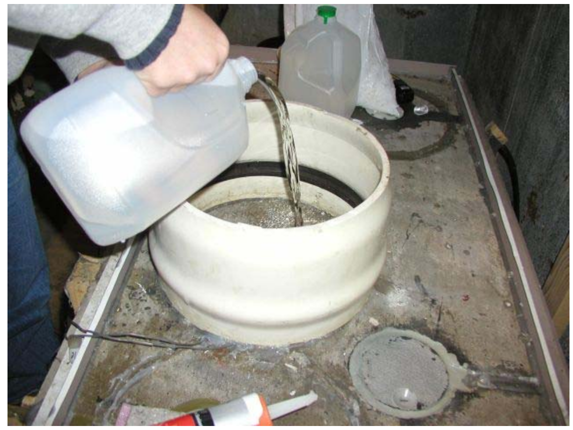


Figure 21. Laboratory Method for Establishing Ice Bath - Pour Distilled Water into Caulked PVC Pipe

Later tests were performed to see whether a plastic bag could hold the bath instead of caulking the edge. The tests were conducted by placing the thermistor baseline directly on the pavement sensor and placing the PVC section over the pavement sensor and thermistor. A plastic bag was then placed over the edges of the PVC as shown in Figure 22. The water and ice were poured into the PVC pipe and stirred.

Three test runs were done with different thicknesses of bags on Sensor A. The first run was done with a 0.95 mil bag, the second with a 0.69 mil bag and the third with a 0.4 mil bag. Following each test run, the pavement sensor was heated back up to roughly 40º F by placing a jug filled with warm water on the sensor. The temperature baseline and sensor with the bag were then compared to the temperature data without the bag.

Figure 22. Field Method for Establishing Ice Bath - Place Plastic Bag Over PVC Section

The graph shown in Figure 23 clarifies two concerns about running the ice bath test with a plastic bag. The first concern is that the bag insulates the sensor against the ice bath. The second concern is whether the bag's thickness affects its insulating properties.

It appears that the water makes better contact with the pavement surface with no bag. The water can contact the rough pavement surface more completely and can even permeate into the pavement to some extent. Using the bag creates tiny air gaps between the bag and the pavement surface that provides an insulating effect. It is apparent that for the bath without the bag, water contacts much more surface area of the top surface of the pavement. The "no bag" data starts very close to the other pavement sensors, but is able to get much closer to 0º C. This shows that the bag affects the results.

Also, the tests show that the thickness of the bag did not significantly impact the rate at which the pavement sensor was cooled. The thinnest bag was a very thin kitchen garbage bag. The thickest bag was a heavy-duty yard waste bag. All data is comparable and shows generally the same shape. Any irregularities in the graph are most likely due to inconsistent stirring.

Figure 23 shows the general pattern of temperature depression when using the bags. While the temperature of both the thermistor baseline and pavement sensors depress at similar rates, clear differences in the final temperature are evident. The graphed unconnected points are the pavement sensor readings and the connected points are the thermistor baselines. The final data series in the legend is a run with a sensor with no bag.

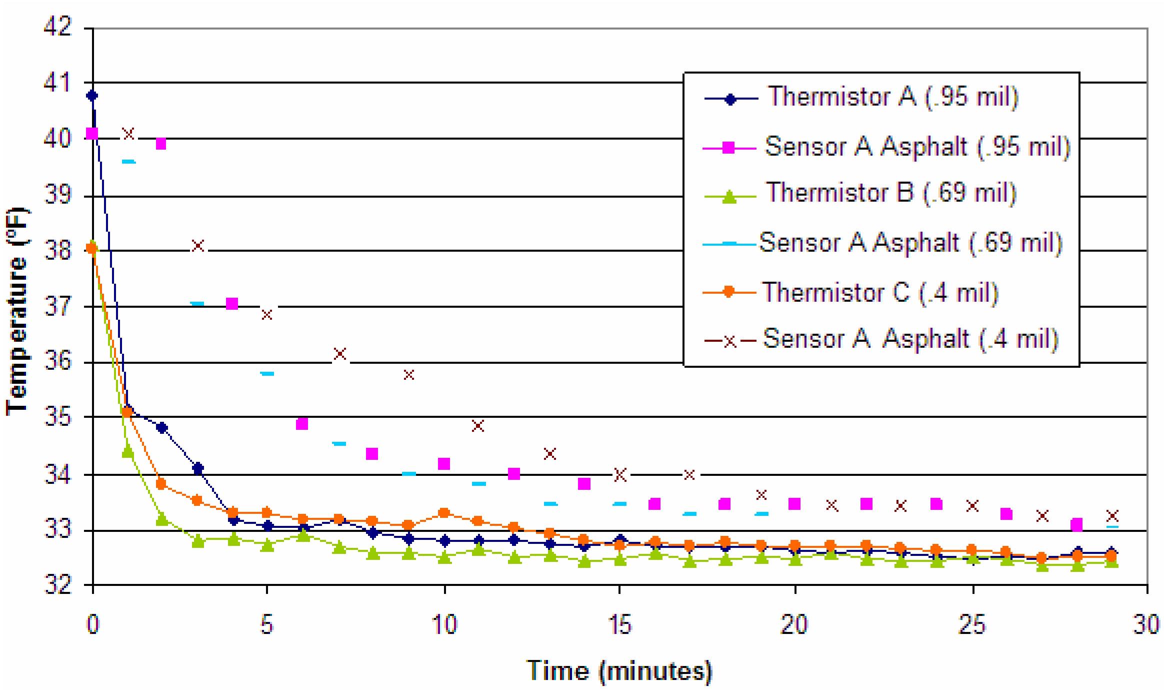


Figure 23. Laboratory Comparison of Different Plastic Bag Thicknesses

The goal of the ice bath test is to force the pavement to a specific temperature that the operator controls. While the bath still depresses the sensor's temperature with the plastic bag, the bath cannot cool the sensor as well as without the bag. However, the precision of this test is not necessarily as important as originally conceived because the ambient temperature test finds temperature accuracy more consistently. Because the temperature sensing elements are generally not much, if any, less accurate around 32º F, additional accuracy data is not very valuable.

The procedure was changed, and it was recommended that the test be modified to include a plastic bag for the field tests. Using the bag, the test may be run much more quickly than without the bag because it is not necessary to create a seal between the PVC and pavement surface. Also silicone caulk is messy and leaves a ring of silicone around the pavement sensor that is difficult to completely remove. This introduces an inconsistency at the site of the pavement sensor. Water that might normally run away from the sensor might be dammed, causing the area to remain wet for longer than it would normally. Conversely, the silicone ring could protect the pavement sensor from water runoff.

After establishing the vessel to contain the ice bath, the operator must add the distilled water or brine and ice. By keeping as many impurities out of the ice bath as possible, it is possible to make the ice bath very close to 32º F. One limitation of this test is that it is very difficult to create a uniform ice bath.

One must take much care in thoroughly stirring the bath to maintain uniform temperature. Before the test is run, it is recommended that the distilled water be chilled so that the ice does not melt as quickly. In order to make a uniform bath, the ice should reach a slush consistency. Using pre-crushed ice is the best way to create a uniform bath. For the lab tests, ice was crushed by putting it in a plastic bag and crushing it with a brick. This does an adequate job in producing small enough chunks with enough surface area to produce a suitable uniform water bath. Other crushing methods may also be used.

Figure 24. Method for Crushing Ice – Place Ice in Durable Plastic Bag and Crush with a Brick

The initial laboratory tests were conducted by preparing the bath, stirring the bath until it was within 0.3º F to 0.4º F of 32º F, and promptly leaving the chamber to record data. It was found that the stabilized 40º F pavement sections slowly warmed the bottom layer of the ice bath and it took close to 30 minutes for the pavement sensor to stabilize. Even after it did stabilize, the bottom layers of the bath did not stabilize as cold as 32º F. This situation failed to establish the close-to-freezing temperature. It is required that the bath be stirred constantly to preserve temperature stability. Otherwise, the ice will float to the top and a temperature gradient will form beneath it. Another run was conducted during which the bath was constantly stirred throughout the testing period. This method allowed the temperatures to get much closer to 32º F.

Sensors with subsurface temperature sensing elements cannot be verified with this test. An effort was made to create a stirred shallow ice bath, which contained mostly ice and would make the pavement colder much more quickly than the ice bath mentioned above. It was found that after hours of stirred ice melting, it was not reasonable to wait for the ice bath to cool the subsurface sensor down to 32º F.

Figure 25. Laboratory Ice Bath - Unsecured Thermistors Do Not Stay In Place When Stirred

Figure 26. Laboratory Ice Bath - Vigorously Stirring Ice Bath Made with Distilled Water and Crushed Ice

As mentioned above, another test was run with a sodium chloride brine bath. This test used an initially saturated brine ice bath to establish a stable temperature even colder than freezing. Another way to accomplish this objective would be to place ice on the sensor, but that method would not be as controllable. As the ice melted, the temperature distribution would change. It is necessary to have a uniform bath to compare bath temperature and sensor readings.

This test was run because a brine bath allows the operator to create a uniform temperature that is colder than water's freezing point. Similar to the distilled water ice bath, the initial tests were not stirred while the data was being recorded. In this case, the thermistor temperatures did exactly the opposite of what the distilled water ice bath did. For the most part, these readings decreased to an eventual stable temperature instead of becoming warmer with time. It may be inferred that this was because the brine solution needed more time to stabilize before the data was recorded.

The temperature of the brine ice bath was so much colder than the distilled water ice bath that the comparatively warmer pavement temperature did not have such a significant impact on heating the ice bath over the duration of the short-term test. The stabilization time for this test was beyond a reasonable time limit for field testing.

Another pitfall of the brine bath is that ice melts throughout the test. This constantly changes the freezing point of the solution. One of the best qualities of the distilled water test is the fact that the bath is a known temperature. With the melting ice, this quality is negated.

In conclusion, only the distilled water ice bath was recommended for evaluation during the field tests because it cools to a known temperature after stabilization. Also, this test is simpler because it does not require a brine solution to be prepared.

Field Ice Bath Tests. Ice bath tests were run in all three of the states. In Minnesota and Nevada, all three operators ran the ice bath test. All tests were generally successful at lowering the temperature close to 32º F, although for one test run in Minnesota, the temperature was colder than 32º F, and the test was stopped early. Based on the results of that test, a note has been added to the Field Test Procedures for Environmental Sensor Stations to only run this test at temperatures warmer than 32º F.

In Pennsylvania, due to time restraints, the ice bath test was performed by one operator on each of the sensors. Because of the physical composition of Sensor C, the ice bath was not effective in lowering the temperature of the pavement sensor. For the particular sensor tested, the temperature resistor is mounted on a circuit board that is suspended in the sensor vessel. The resistor makes little physical contact with the edges of the sensor or the top of the sensor where the ice bath was placed. It was learned from the manufacturer representative that in a newer version of the sensor, the thermistor element is close to the top of the sensor to better record pavement temperature at the pavement surface. Needless to say, the ice bath had little effect on this sensor. Figure 27 shows that the temperature did not change after the ice bath had been applied. This example reinforces the fact that when deciding to run these tests, the operator must think about the physical processes of the tests. The procedures can be applied to most sensors, but not all universally.

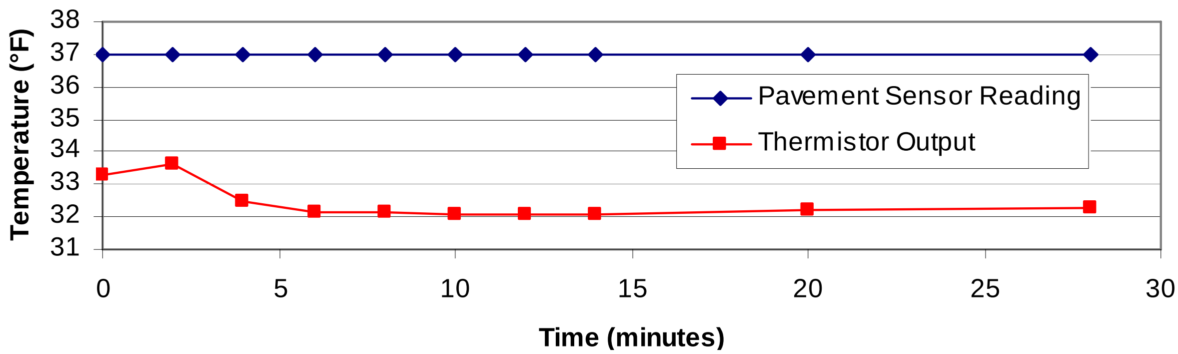


Figure 27. Sensor C Ice Bath Field Test

When the ice bath was applied to pavement sensors they reacted gradually. The elapsed time for the sensor to approach the ice bath temperature depends on the starting temperature and performance of the sensor system in the testing environment. Table 24 shows if the sensor was responsive or not and how long the sensor took to approaching 32º F. The convergence index (CI) was used to quantify the convergence. The accuracy is the difference between the temperature of testing thermistor and that of pavement sensor at 90 percent of CI.

To statistically analyze this data, more complex measure than error is required because the temperature is constantly changing throughout the test. The measure that was selected is called the convergence index (CI) and is defined as the following:

$$CI = \frac{T_{start} - T_{current}}{T_{start} - 32}$$

*The index will approach +1 from the positive side.

The tests run in Minnesota and Nevada can be compared in this way. As mentioned, one of the tests done in Minnesota started colder than 32º F and did not converge. It is also hard to tell if the sensor was responsive, because relatively few data points were collected.

Table 24. Sensor Responsiveness and Accuracy for Field Tests (°F)

Operator	Sensor Type					
	MN-A		NV-B		PA-C	
	Responsiveness	Accuracy	Responsiveness	Accuracy	Responsiveness	Accuracy
A	Yes	1.18	Yes	1.93	N	N
B	NC	NC	Yes	4.86	NA	NA
C	Yes	0.96	Yes	2.75	NA	NA

*NC denotes that the analysis had no convergence
*N denotes that the sensor was non-responsive
*NA denotes that the analysis was not applicable

Dry Ice Tests

Laboratory Dry Ice Tests. Dry ice was also used to cool the pavement sensor and find a correlation between a baseline and the pavement sensor. Dry ice forced the pavement sensors to a much colder temperature than an ice bath or the environmental chamber could. Dry ice sublimes at approximately -109º F, meaning that while it is a solid, it remains colder than that temperature. As time progresses, the solid sublimes and becomes a gas. Because the dry ice is so cold and can make the pavement sensor cold, this test shows how the pavement sensors react to extremely cold temperatures The test could simulate an extreme weather situation and would show that the sensors can respond to such extreme temperatures, allowing the user to determine if there are range limitations in the ESS software or hardware.

Initial laboratory tests were run with small 5”x5” blocks of dry ice which often barely covered the sensor’s surface. It was determined that such small blocks sublimed too quickly and tended to drift from their initial positions on the sensors. Initial tests also showed that thermistor baselines were not useful. The block of dry ice rested on the thermistor and caused the pavement section and the sensor to cool unevenly. Partially because of this difference, there was a fairly wide distribution in the minimum temperatures that the thermistors measured. From this finding, it was established that this test should not measure accuracy at cold temperatures.

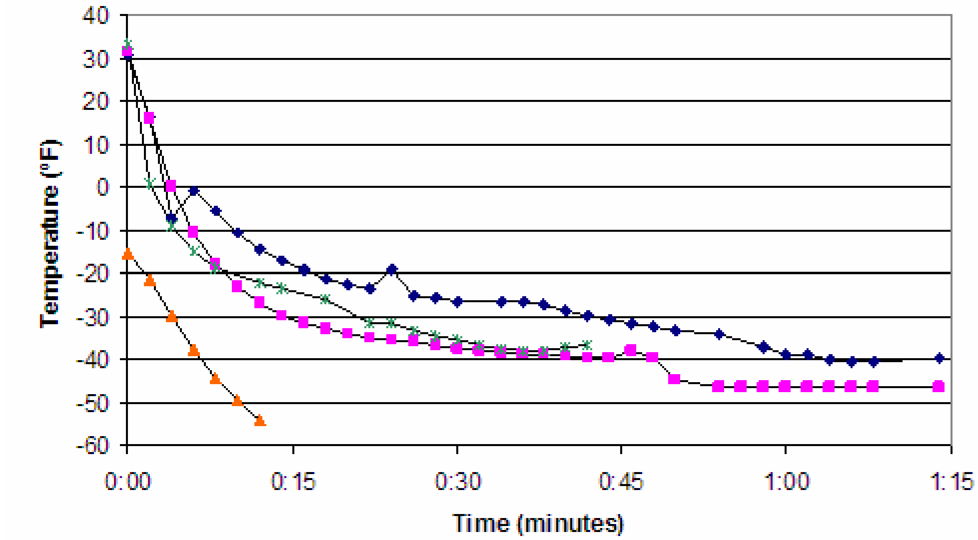


Figure 28. Laboratory Test – Temperature Comparison for Four Sensors Subjected to Dry Ice

There was also variability in the amount of cooling that the dry ice did. Some of this variability is shown in Figure 28, which is a comparison of four sensors embedded in asphalt. The difference in temperatures is based on a few factors that exhibit complicated thermal processes, such as the sublimed carbon dioxide gas insulating the sensor from the dry ice. Pavement sensors are not designed to take on new temperatures in this way.

Two major factors that affect how fast the new temperature will propagate through the sensor are the material type of the sensor and the type of contact that the dry ice made with the pavement sensor. For example, a rough surface will not transfer the cold temperature the same as a smooth surface. A possible reason for this inconsistency is that as the dry ice sublimes and becomes a gas, a thin layer of gas may insulate the dry ice from the pavement. The dry ice forms to the shape of the pavement. This prevents the pavement from becoming as cold as the dry ice. This phenomenon is shown in Figure 29 that shows the imprint of Sensor A on the bottom side of the dry ice.

Figure 29. Imprint of Pavement Surface on Bottom Surface of Dry Ice

Previous testing on the same sensors sponsored by the Aurora Consortium found that these sensors are approximately equally accurate at all temperatures within the sensor's valid range. This test simply found the range in which sensors can perform such cold readings.

Additional testing was done with full 10" x 10" dry ice blocks and without thermistor baselines as shown in Figures 30 and 31. Results of these tests were similar to the previous tests, except that the dry ice lasted longer. It was concluded that as long as the block does not drift away or completely sublime, the size of the block is not important.

Figure 30. Applying Full 10" x 10" Block of Dry Ice to Pavement Sensor

Figure 31. Dry Ice Cooling Asphalt Pavement Sensors

It was also determined that in order to bring the temperature of the sensors back up to ambient temperature, it took more than 30 minutes. Thus, this test must be run last because it would foul any subsequent tests until the pavement section restabilized.

Field Dry Ice Tests. Of the four sensors tested, none of the sensor manufacturers recommended running the dry ice test. Despite these concerns, operators in Minnesota and Nevada were allowed to run the test on Sensor A and Sensor B respectively. The results of these tests were very similar to the lab tests. In Pennsylvania, the manufacturers strongly recommended against using dry ice and no tests were conducted. The data that was obtained in Minnesota and Nevada was consistent with the laboratory data. Additional testing would have likely led to similar results.

The dry ice test was run one time in Minnesota. During this test, the pavement sensor started around 25º F and was cooled to around -45º F. A graph of this data is shown in Figure 32. In Nevada, the test was run by all three operators. A graph of that data is shown in Figure 33. Two of the runs exhibited very similar patterns in cooling rates. The other run did not cool as fast. This shows that even between operators using the same equipment, there can be some variability. This is most likely due to the amount of contact that the dry ice made with the pavement sensor surface. If a void occurred between the pavement sensor and dry ice, the pavement sensor would have cooled more slowly or not cooled down as far as one with good thermal contact.

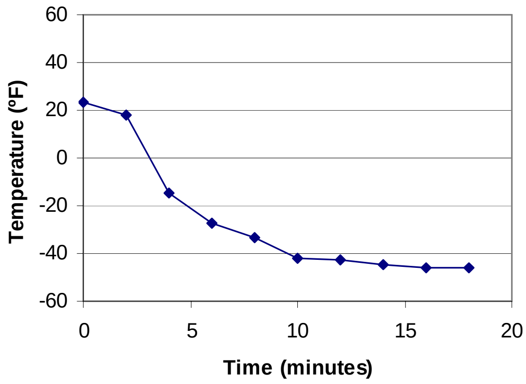


Figure 32. Graph of Results of Dry Ice Test Conducted in Minnesota

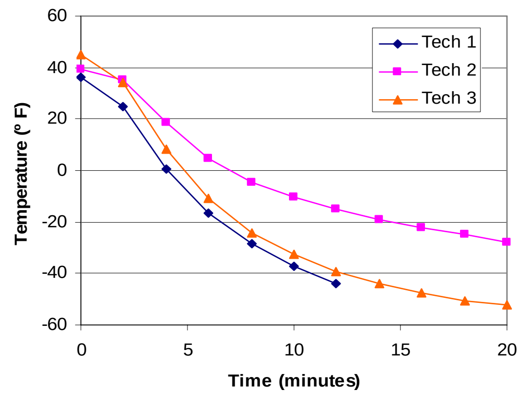


Figure 33. Graph of Results of Dry Ice Test Conducted in Nevada

To statistically analyze this data and to quantify the cooling rate, the linear regression method was used to define the simple quadratic curve between time and temperature. Table 25 shows the estimates of the unknown parameters in the quadratic equation explained above. The cooling rates in Table 25 were determined by taking the derivatives of the quadratic equation.

Table 25. Quadratic Equation Parameters for Nevada Field Test

Sensor	Operator	β_0	β_1	β_{11}	Adjusted R2	Cooling Rate
NV-B	1	4.233	-6.134	0.185	0.987	Moderate
	2	5.869	-3.868	0.098	0.984	Moderate
	3	8.803	-6.139	0.172	0.989	Slow

In addition to the time required to run the test, additional time is required to bring the pavement back to a reasonable temperature to run additional tests. During one of the Nevada tests, the dry ice was removed from the sensor, and data was recorded for an additional 10 minutes to see what the temperature recovery time might be. This data is shown in Figure 34. In this figure, the vertex of the graphed data is the last point in which dry ice was on the sensor. Immediately after this point, the dry ice was removed from the pavement, and the pavement sensor began to warm. As shown in the graph, the warming is quick at first, but begins to slow down. It looks as though the graph has an asymptotic shape as it approaches the ambient temperature. This recovery time may not allow the tests to be run efficiently unless the dry ice test is run last.

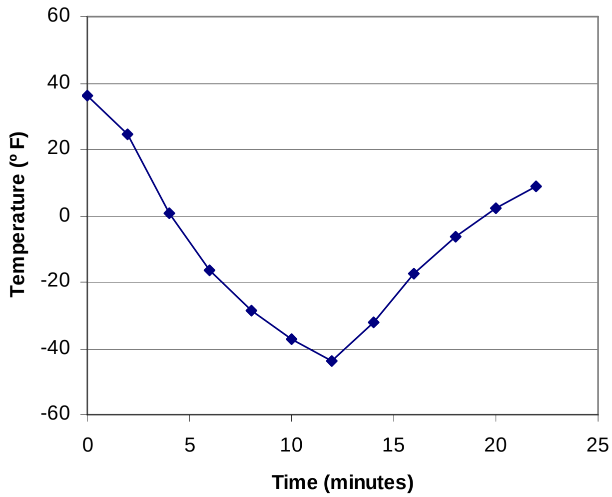


Figure 34. Graph Showing Temperature Recovery of a Sensor after the Dry Ice Test

As mentioned, this test met a considerable amount of opposition from the sensor manufacturers. The most universal argument was the possibility of the dry ice throwing the sensor out of calibration or ruining the electronics of the sensor. This is a valid argument, though the laboratory testing showed that this was not the case. Additional laboratory temperature accuracy testing was conducted after the dry ice tests and showed no less accuracy.

Because it is important that the final test procedures are accepted among manufacturers and agencies alike, this test was not included in the Field Test Procedures for Environmental Sensor Stations. Beyond exercising the sensor to see how low it can go, this test has comparatively less value than the other tests run in the field. If an agency would like to try these test procedures and do additional research on this test method, the field test procedures are included as Appendix H – Field Test Plan.

Surface State Tests

Frost Tests

This test verifies that a sensor can identify a frost condition. The general test procedure is to take a visual observation of the pavement surface and compare it to the RPU reading. Both in the laboratory and the field, operators had great difficulty testing this surface state. In the laboratory, various procedures were tested, but no method was able to produce measurable frost. In the field, the frost needed to have formed before or during testing. Frost conditions were not observed during the eight days of field testing.

Additionally, fewer sensors report frost condition than other surface states, such as wet/dry. Thus, this procedure has not been included as a stand-alone procedure in the Field Test Procedures for Environmental Sensor Stations. Instead, it has been integrated in the set-up procedures. The method is now to verify the surface state condition when setting up the sensor. If frost is visible, it will be verified and recorded in the sensor set-up documentation.

Laboratory Frost Tests. It was difficult to produce adequate frost on the sensors with the procedures in the Validation Test Plan. A few methods were tried. One method used the environmental chamber to cool the pavement sections and then open the chamber door to let warm air enter the chamber. Moisture from the warmer air should have condensed on the sensors and eventually produce frost. This method produced some condensation on the sensors, but no measurable frost.

Another method used hot water to produce a very humid atmosphere in the environmental chamber. A large cooler chest was filled with very hot water and was brought into the chamber and the chamber was closed. The hot water was splashed and stirred in the chamber in an effort to add additional moisture to the air. Despite these efforts, laboratory testing was not able to produce frost formation on the sensors.

Field Frost Tests. As in the laboratory tests, frost was not present on any of the days of the field tests. For field tests, the best time to see frost is early morning after the pavement has cooled overnight. On each testing day, as soon as the test equipment was set up, the operator checked the pavement sensor reading from the RPU and took a visual surface state reading. In each case, the pavement temperature was greater than the dew point temperature and frost was not present. Typical differences between pavement temperature and dew point temperature that were encountered were in the range of 2º to 10º F.

Further compounding the difficulties of running this test are the fact that frost forms on the top layer of pavement, which is most exposed to air currents and solar radiation. As vehicles pass over the sensor, they generate air currents that dry the pavement. Thus, while frost may be an important surface state that forms on roadways, it is not common enough to be able to reliably test. Because the test procedures have been designed to be run on any given day, it is not reasonable for the operator to expect to have a frost condition.

Wet, Dry and Ice Surface States

The general procedure for the Wet, Dry and Ice Surface States test was to apply a known surface state to the pavement sensor and see if it reacts. Additionally, during the laboratory and field testing, time-related data was also measured to see how long it takes for the sensors to report the condition.

There are a few concerns for this method of applying a known surface state to the pavement sensor site. The most prominent concern is that the RPU often takes other information into account when reporting surface states. Often, the RPU uses atmospheric and pavement sensor data. Sometimes the atmospheric sensor data supersedes the pavement sensor data. For these cases, on a clear day, the pavement sensor will not report a wet state despite the fact that the pavement sensor reports a wet condition. Of course, there are ways to fool the atmospheric sensor, such as introducing snow or water into the sensor, but these methods could be difficult to execute and were not tested. For each of the field tests, an expert on the particular sensor, such as a vendor, was on hand and this is recommended if the proper condition cannot be attained by using only the provided test methods in the Field Test Procedures for Environmental Sensor Stations.

Other concerns are illustrated in the following sections about the laboratory and field tests.

Laboratory Wet, Dry and Ice Tests. As mentioned, in the laboratory, the three surface states were performed as separate tests. The dry tests basically called for the operator to hand-dry the sensor surface. The sensors read wet or dry based on electrical voltage passing through two electrodes. If the road is dry, electrodes will not pass any electricity. When the road is wet, although pure water is an insulator, it is assumed that the water on a road will not be pure and will conduct electricity. Salts and other impurities, even in small quantities, provide a medium for electricity to pass through.

The “wet” test called for the operator to spray a film of tap water on the sensor. The pavement section in the environmental chamber was again set at 40º F. This temperature was chosen because it is warmer than water’s freezing point and not so warm as to possibly evaporate the water off the sensor in case the test would be run for a long period of time.

The ice test was run similarly to the wet test, but the chamber was set at 20º F so that the water would freeze. Again, tap water was sprayed on the sensor surface. The water was allowed to freeze and sensor readings were taken. Ice was easily reproducible on the sensor surface. When the sensors are below freezing, tap water in a thin film freezes quickly on the surface of the sensor. It is not immediately clear how the sensor knows that there is ice, and it is probable that different sensors use different measurement methods. One possible method would be to use temperature and conductivity as inputs. The sensor would read the water on the road and decide that it is ice or water based on the temperature. This is only a hypothesis, and it is known that at least one other sensor does not use conductivity to determine surface state.

In all cases in the laboratory environment, the sensors that were properly installed and set up gave good results. In some cases, even after the water had evaporated and was not visible on the sensor, the sensor still read wet. This could be due to residual salt on the sensor serving as a medium for conductance or a humid condition that, while not visible, was apparent by touching the sensor. It was then sometimes necessary to dry the sensor with a cloth or paper towel to obtain the dry condition. This may not be such an issue in the field because solar radiation and wind will be present.

Field Wet, Dry and Ice Tests. For field testing, the test was modified from its original laboratory test form to run faster. Instead of running the tests separately, the dry, wet and ice surface state tests were combined. To conduct the dry surface state test, the pavement sensor was thoroughly dried with a paper towel and then RPU readings were taken. To conduct the wet surface state test, water was sprayed on the sensor and RPU readings were taken. Finally, the water was allowed to freeze if temperature conditions permitted and RPU readings were taken. The consolidation of this test greatly reduced the amount of time it took for the operators to run the test. Each of these tests was run twice in the field.

The field operators ran this group of tests very effectively by the field operators. It required little time and produced adequate results in most cases. For the only case where it did not provide adequate results, inclement weather was a major factor, because it influenced the atmospheric sensors.

As time was an issue and the bridge that the pavement sensor was installed on was completely closed to traffic, testing was conducted despite the poor weather conditions. Readings were taken at this site by removing the RPU's surface state algorithm from the information chain and taking voltage readings directly from the sensor. The RPU receives these voltages and uses them to determine surface state. The manufacturer technician who helped the operators access the RPU information was able to run a program that showed live voltage readings. Some of these programs might not be available to ESS users and would require the manufacturer to be on hand.

If this problem is encountered in the future and the manufacturer is not available, one possible solution could be to disconnect the proper leads from the sensor to the RPU and take a voltage reading across the two wires. Based on how significant the voltage change is between the wires, an evaluation could be made about whether the sensor can give an appropriate reading. This is not an optimal situation, but it did allow testing to proceed. The temperature for this test was above 32º F, so ice testing would not have been possible.

A repeatability and reproducibility analysis for each method is presented in Tables 26 and 27. Because the tests were integrated, they now have a process that is conducted as follows. The test starts relatively dry and required little or no effort to dry. Readings were taken. The tap water was sprayed on the sensor, which reported the wet condition within one or two readings. The sensor was then thoroughly dried and two methods were evaluated—paper towel and heat gun. Readings were taken. The sensor was wet again and readings were taken. Finally, if the weather permitted, which it did in a couple cases in the Minnesota testing, the water was allowed to freeze and readings were taken each cycle until the ice condition was read.

Another concern is that with some sensors, the drying procedure requires care. In the interest of efficiency, a heat gun was added to the field test drying procedure. Although it is necessary to get power to the sensor site, when this can be accomplished, the heat gun can completely dry a sensor very quickly as explained in the following section on field test results.

Figure 35. Drying a Pavement Sensor with a Heat Gun

All tests have good repeatability and reproducibility except the dry to wet with a paper towel. Because this test was not as reliable at drying the sensor, it is less repeatable and reproducible. Because the rest of the tests are repeatable and reproducible, response time—the time for the sensor to report the new condition—is an important analysis factor. These response times have been built into the Field Test Procedures for Environmental Sensor Stations so that the tests will provide meaningful results.

Table 26. Repeatability of Field Test Methods

Method		Sensor Type				Time (min)
		MN-A	NV-B	PA-C	PA-D	
Dry	Start	Yes	Yes	Yes	Yes	0
Dry to Wet	Tap water	Yes	Yes	Yes	Yes	2-4
	Tap water-soaked paper towel	NA	Yes	NA	NA	2-4
Wet to Dry	Paper Towel	NA	Yes	NA	NA	6-20
	Heat Gun	NA	Yes	Yes	Yes	2-8
Ice Formation		Yes	NA	NA	NA	0

Table 27. Reproducibility of Field Test Methods

Method		Sensor Type				Time (min)
		MN-A	NV-B	PA-C	PA-D	
Dry	Start	Yes	Yes	Yes	Yes	0
Dry to Wet	Tap water	Yes	Yes	Yes	Yes	2-4
	Tap water-soaked paper towel	NA	Yes	NA	NA	2-4
Wet to Dry	Paper Towel	NA	No	NA	NA	6-20
	Heat Gun	NA	Yes	Yes	Yes	2-8
Ice Formation		Yes	NA	NA	NA	0

Tests that require long response times are not as efficient to run. Response time is shown to be negligible except in the case of the paper towel. Other methods require a maximum of three to four two-minute cycles to report the condition. This test method had repeatability but did not have reproducibility. The paper towel drying method requires up to 20 minutes to report the dry condition. For efficiency, only a heat gun is recommended if power is available.

This means that the test could be repeated by the same operator, but not necessarily reproduced by a different operator. This drives at the fact that different people give more care to drying the sensor and have different results with the paper towel. It could also mean that different sensors require different amounts of care in drying.

Passive Sensor Freezing Point Tests

The following sections analyze the test methods for sensors that passively detect a freezing point temperature of a chemical solution on the sensor.

Laboratory Passive Sensor Freezing Point Tests. In the laboratory validation testing, the passive sensors were tested at four different brine concentrations: 4 percent, 10 percent, 15 percent and saturated sodium chloride solutions. The brines were applied to the sensors with a spray bottle to a depth of 0.5 mm. Electrodes in the passive sensors report a conductance which sensor software converts to freezing point.

Concerning freezing point stabilization time, when the passive sensors were working properly and reported the depression, they registered very close to their stabilized reading within no more than eight minutes. Because of the electrical process that the sensors use to determine freezing point, it may be reasonable to eliminate the freezing point stability criteria. For example, one sensor applies an alternating current to the two electrodes. Based on the voltage that the two inner electrodes measure, the salt concentration may be calculated. The computer then displays the freezing point for the end user. Similarly, other passive sensors use conductance to find the freezing point.

Although extensive laboratory testing of passive sensors' ability to provide freezing point was conducted in a laboratory environment, none of the three sensors tested were able to provide reasonable freeze point data using the method described in the Laboratory Validation Test Plan. Results were better with the lower concentrations. From these findings, it was decided that the field tests would concentrate on the low concentration solutions, because better accuracy was obtained in the laboratory tests.

As a result, we were not able to develop test procedures that provided useful information about the sensor accuracy of the sensor. Applying the original procedures may even lead to conclusions that the sensor is faulty when this is not the case. It was demonstrated in the laboratory that passive sensors have individual quirks, and one procedure could not universally apply to all passive sensors.

Field Passive Sensor Freezing Point Tests. Two passive sensors were tested in field tests in Minnesota and Nevada. The two faired very differently due to their physical configuration. Three factors were analyzed to understand the results of the test method:

accuracy, precision and repeatability. Of the two sensors, Sensor A was more consistent than Sensor B in the field tests. Prior to testing, Sensor A's vendor gave the recommendation to fill the well with the solution before running the field tests in Minnesota. This was different than the protocol used in the laboratory test where a film was used. This recommendation produced accurate results at low concentrations that were found to be repeatable, although the readings at high concentrations were less accurate.

First, the accuracy and precision of the two sensors is analyzed. Table 28 summarizes the precision and accuracy found in the field tests.

Table 28. Precision and Accuracy of Passive Sensor Testing Methods—Absolute Error from Theoretical Baseline (°F)

Test Method	Precision		Accuracy	
	MN-A	NV-B	MN-A	NV-B
1%	Not Available	0.36	Not Available	2.17
4%	0.02	0.64	0.31	3.23
10%	0.12	2.85	1.26	9.47
15%	0.12	1.41	3.38	7.00
Saturated	0.45	Not Available	13.15	Not Available

Both precision and accuracy decrease with higher concentrations. These figures were converted to points as explained in the testing Test Selection Matrix in section of Chapter 2. The precision and accuracy measurements shown in Table 29 were normalized using the selection factors developed.

Table 29. Performance Factors of Field Test Methods

Test Method	Precision			Accuracy		
	MN-A	NV-B	Both	MN-A	NV-B	Both
1%	Not Available	6	6.0	3	Not Available	3.0
4%	10	5	7.5	2	8	5.0
10%	7	3	5.0	0	4	2.0
15%	7	4	5.5	0	2	1.0
Saturated	6	Not Available	6.0	Not Available	0	0.0

Graphs show how the data became less precise and accurate with increased concentrations. The first set of graphs is from the tests run in Minnesota. As shown in the

Figures 36 – 39, the data is very close to the baseline for the lower concentrations, but becomes less accurate at the highest concentrations. At the highest concentrations, the data is significantly greater than the baseline. The runs are in chronological order, but do not necessarily correspond with any certain operator.

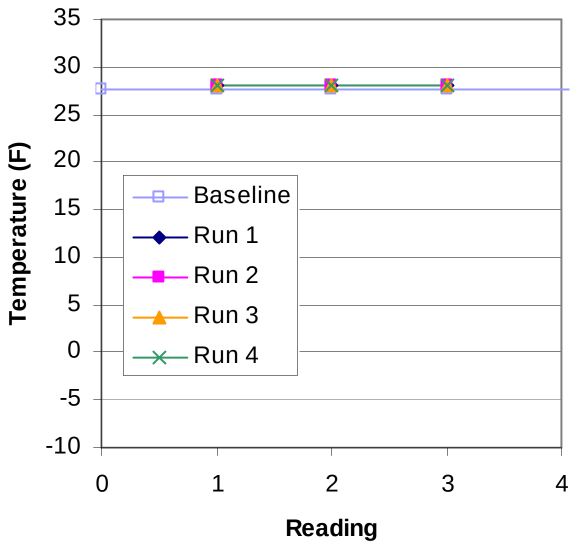


Figure 36. Passive Sensor Results with Sensor A Using a 4 Percent Sodium Chloride Solution

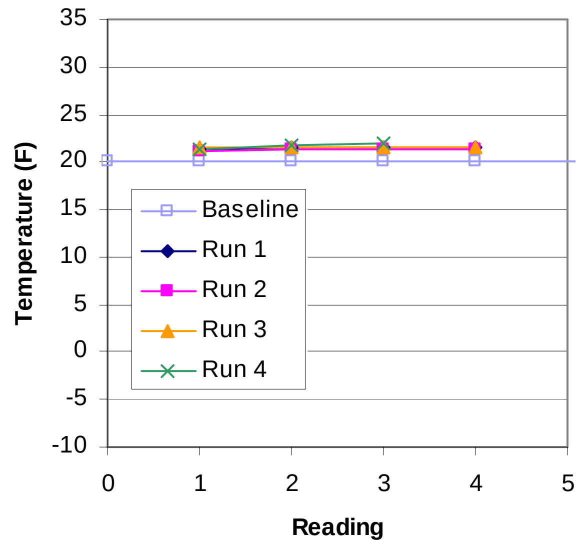


Figure 37. Passive Sensor Results with Sensor A Using a 10 Percent Sodium Chloride Solution

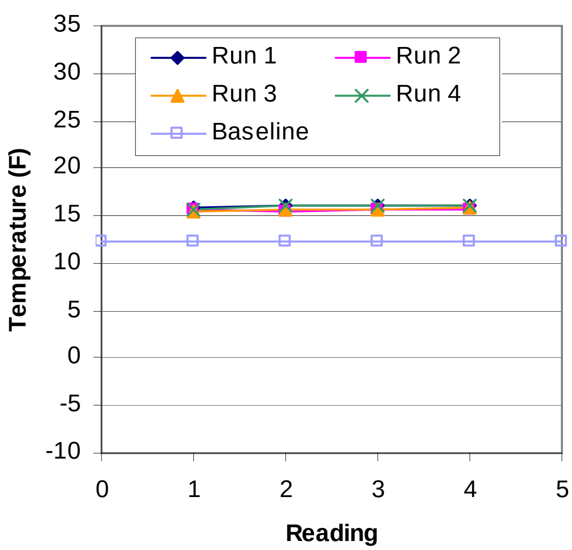


Figure 38. Passive Sensor Results with Sensor A Using a 15 Percent Sodium Chloride Solution

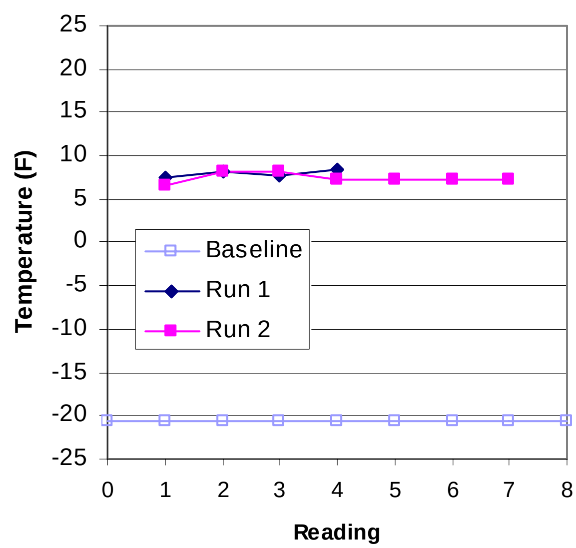


Figure 39. Passive Sensor Results with Sensor A Using a Saturated Sodium Chloride Solution

The other passive sensor showed more variation in its readings. Sensor B tested in Nevada did not have a well like the Sensor A. Figures 40 – 42 show how the pavement sensor accuracy and precision become worse with higher concentrations of solution. Again, the data sets are runs in chronological order. Any given run does not necessarily correlate with a given operator. A general trend that was identified was that the more care the operator took in cleaning the pavement surface, the better the results were. From this finding, it is advised that the sensor site be repeatedly flushed with distilled water to remove any impurities from the sensor site before applying the solution. The sensor must also be thoroughly dried before applying the solution.

One problem that may also have caused some inconsistency is that the solution ran from the sensor site because of the crown of the roadway. A paper towel was laid on the pavement before the sensor was sprayed and the paper towel absorbed the solution. This has possible accuracy ramifications in that it is more difficult to measure the thickness of the film. This was a necessary step in proceeding with the field testing, and the method looks to have been somewhat effective.

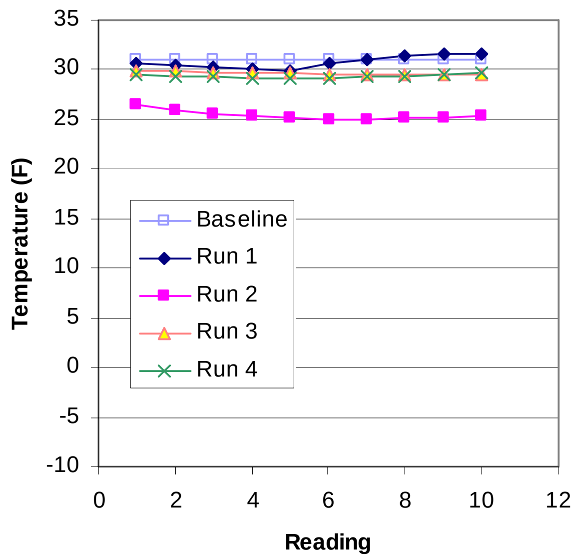


Figure 40. Passive Sensor Results with Sensor B using a 4 Percent Sodium Chloride Solution

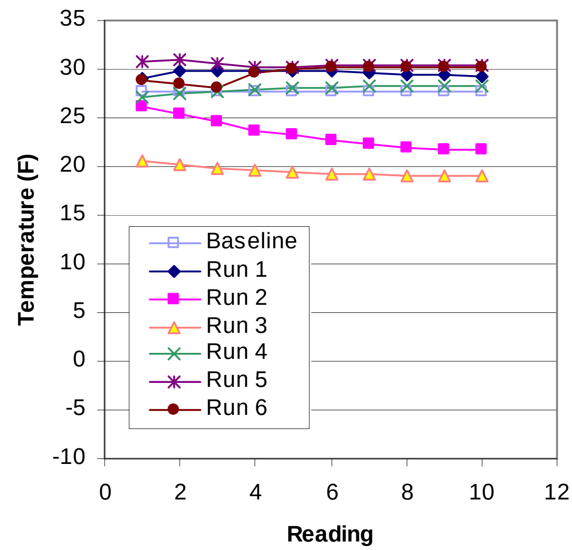


Figure 41. Passive Sensor Results with Sensor B using a 10 Percent Sodium Chloride Solution.

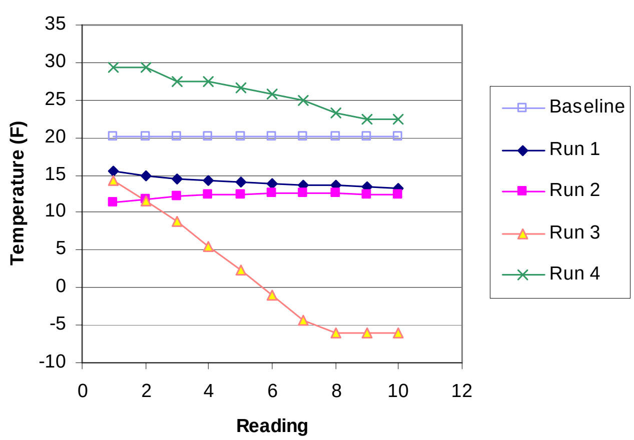


Figure 42. Passive Sensor Results with Sensor B using a 15 Percent Sodium Chloride Solution

Although Sensor C's vendor makes a pavement sensor that can measure freezing point, the model that was tested in Pennsylvania did not have that capability.

In order to determine the accuracy requirement for the Field Test Procedures for Environmental Sensor Stations, the Nevada data using the 4 percent concentration was analyzed because it had a higher baseline/pavement sensor difference than the Sensor A.

Because absolute error was used to analyze errors in one direction while deviations in the other direction were ignored, it is appropriate to use a one-tailed method to establish the confidence limits. Using a sample size of four readings for the four stable points required in the Field Test Procedures for Environmental Sensor Stations, the required accuracy for 95% confidence is 3.5° F (2.0° C). Calculations are provided in Appendix K.

The other factor that was analyzed was repeatability. A summary of the repeatability of the two sensors is shown in Table 30.

Table 30. Required Error Tolerances for Repeatability by Operator

Test Method	Sensor Type			
	MN-A	NV-B		
	Operator 1	Operator 1	Operator 2	Operator 3
1%	Not Available	Not Available	9.88	2.89
4%	0.30	16.44	8.02	9.54
10%	1.71	9.61	Not Available	Not Available
15%	2.08	Not Available	Not Available	Not Available

The values in this table are the amount of error tolerance required for repeatability for each operator who had two or more runs. For this measure, operators that had lower "required error tolerance" found more repeatable results. As shown in the table, all Sensor A tests and Operator 3 of the Sensor B tests at the one percent concentration had high repeatability. This shows that for the same operator on the same sensor, the operator should be able to produce the same results given an allowed tolerance

The repeatability analysis was performed for each operator with at least two runs, of which the average standard deviation was corrected based on the number of data in each run. Since the upper and lower specification limits were not available, the difference between the limits, called the error tolerance, was determined by assuming a precision-to-tolerance ratio of 0.3.

The research team believes that the repeatability of the Sensor A tests is because it uses a well and not a film like the other sensors. While some would say that the well becomes less accurate with field conditions, such as sand and ice, this sensor produced the most repeatable results. While the tests make no claim as to whether the data this sensor collects is accurate, the tests can validate that the sensor is calibrated properly.

Because there was not enough data or a low error tolerance in repeatability and reproducibility, a one-way ANOVA was used to determine the statistical significance of variation due to operators. As shown in Table 31, there was a statistically significant difference between operators for the Nevada tests, but not for the Minnesota tests. This difference could be because the two sensors had slightly different configurations and used a slightly different test method.

Table 31. ANOVA Significance Between Operators

Test Method	Sensor Type	
	MN-A	NV-B
1%	Not Available	Yes
4%	No	Yes
10%	No	Yes
15%	Y at 5% confidence interval N at 1% confidence interval	Not Available
Saturated	No	Not Available

Active Sensor Freezing Point Tests

Active sensors were also tested. The active sensor is different from a passive sensor because an active sensor warms and cools the sensor's surface cyclically to melt or freeze chemical solution or water on the sensor to determine its freezing point.

Laboratory Active Sensor Freezing Point Tests. The one active sensor in the test faired well in determining freezing point. Tests on this sensor show that it gives quite accurate readings for four percent to 15 percent solutions. Refer to Appendix H for detailed results.

However, one test run with saturated sodium chloride reported about 15 percent instead of the 23 percent that it should have. This may be caused by an inconsistent film of water due to beading on the sensor surface and eventual runoff from the sensor. Sodium chloride is a strong electrolyte that increases the surface tension of the water. While the change in surface tension is not profound, it makes the water bead more than pure water. Because of the beading property, water that would normally be evenly distributed on the sensor surface becomes concentrated in some areas. This produces an uneven distribution of water on the surface that affects the active sensor's accuracy. Based on this finding, active sensors were tested with a 10 percent sodium chloride solution. This gives a concentrated solution that does not have the surface tension problems that the more concentrated solutions have.

Field Active Sensor Freezing Point Tests. The only test that was conducted on an active sensor was done in Pennsylvania. Because of the time required to test an active sensor, only limited testing was completed. A 10 percent sodium chloride solution was used, and the sensor reported between 21.5º F and 23.1º F. The actual freezing point of 10 percent solution is 20.2º F. It is difficult to say how the approximately 2º to 3º error was introduced. It will be up to the individual agencies to determine an appropriate error. A recommendation of 3º is recommended in the Field Testing Procedures for Environmental Sensor Stations, but because limited data was available, it is not possible to run statistical analyses for this test. Table 32 presents the freezing point readings taken with the 10 percent solution.

Table 32. Active Sensor Readings of 10 Percent Sodium Chloride

Operator	Run	Freezing Point Reported by Active Sensor (º F)
A	1	23.1
A	2	23.1
B	1	22.0
B	2	22.2
Baseline		20.2

The active pavement sensor gave stable readings on its first reading and did not need time to stabilize. This was positive for the time required to run the test, but the Field Test Procedures for Environmental Sensor Stations still require that three readings be taken before stopping the test.

Additional testing was conducted on the active sensor while the other tests were run on the passive sensor. At the particular testing site, the sensors are located more than 10 feet from each other. As long as the passive sensor is within a proper range, the active sensor is activated. The additional testing was done with a four percent solution to understand the stability of the active sensor's reading. As shown in the graph in Figure 43, the solution remained stable. During this time, the sensor was covered by a bucket to protect it from precipitation and wind. The graph shows that the active sensor can remain stable. The average reading over this period of 105 minutes was 28.5º F. A four percent solution of sodium chloride has a freezing point of 27.7º F.

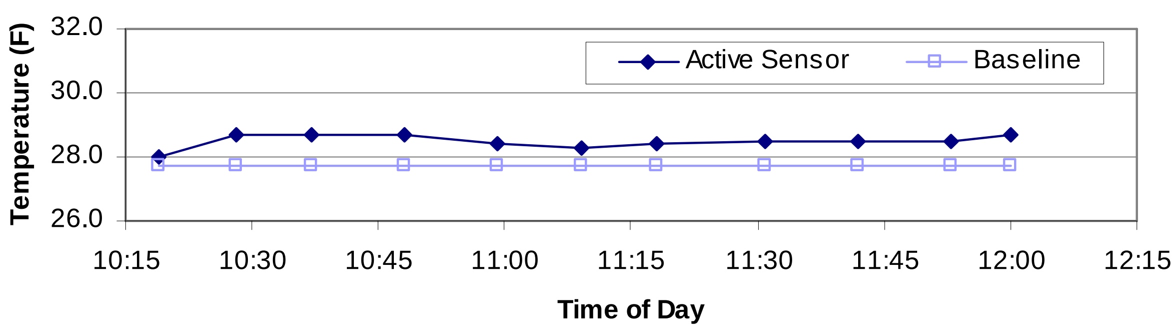


Figure 43. Graph Showing Active Sensor Stability over a Long Duration

One concern with running this test over a long period of time is that the solution on the pavement sensor may begin to evaporate with each heating cycle. This factor may have been more important if the weather conditions had been warmer. The weather conditions were around 33º F. Warmer conditions may not have triggered the active sensor to run.

Interview Results

All three operators in the Minnesota tests had experience maintaining ESS stations. Two of the three operators in Nevada used RWIS regularly, and the third operator had been trained to use it. Only one operator had experience working with ESS equipment in the field. In Pennsylvania, the operators had minimal experience using RWIS information and working with the ESS equipment in the field. In summary, each state treats staffing RWIS differently, and the test procedures were completed by people of varying knowledge and use of RWIS systems.

Other questions were asked about testing experience and level of comfort using step-by-step instructions. Almost all the operators reported some testing experience. This experience ranged from electronics testing to construction materials testing. All operators claimed to work well by following step-by-step instructions.

Experience using the data from RWIS systems varied from operator to operator. All operators knew how to access their state's RWIS information, but their position determined how the information was used. While one operator used RWIS information to determine whom to send out in a storm event, some operators only used the information to see the road conditions before personal trips. No operators use RWIS on a vehicle and few use the information for forecasting. Periodic quality control is done by those who see the information the most. It was inferred that sensors that are thought to be inaccurate are not often quickly fixed. Generally, the maintenance is done on all the sensors during a given period.

The operators each evaluated the baselines. All were confident in the readings that the thermistor baseline took, though few of them could identify a time when they used a thermistor baseline. The operators were less confident in the infrared gun baseline, though some operators were impressed with the accuracy considering their previous experience with infrared guns. Of those who ran the tests above 32º F, the operators generally preferred the contact infrared gun to the distance infrared gun because it gave one reading and did not float between readings.

Many questions were asked of the operators to improve the tests or make them easier to run. Few operators could identify ways to change the tests, although possible changes were noted throughout the procedure and reviewed after each round of testing. These changes are noted throughout the field testing results and have been integrated where necessary in the Field Test Procedures for Environmental Sensor Stations. After running the tests, the operators were confident that the tests accurately tested the pavement sensors.

The operators were also asked to evaluate the training and guidelines. They all found the training to be clear, but some operators had questions during the testing. These questions were answered by the research team, but many of them could have been answered with the provided documentation. Directions that were unclear were revised for the Field Test Procedures for Environmental Sensor Stations.

The operators all felt that the training helped them run the tests. While two of the nine operators said that they could have completed the procedures without training, the general consensus was that it would be much easier and efficient to run the tests after having received some training.

In Minnesota and Nevada, the operators were asked to prepare sodium chloride solutions for the field tests. In Pennsylvania, a chemistry laboratory prepared the solutions ahead of time because a scale was not available. The operators who were asked to prepare the solutions had no problems doing so, though the 100 mL graduated cylinder used to check the solution concentrations was not tall enough to take the lowest concentration hydrometer readings. One solution to this problem is to buy a bigger volume graduated cylinder and prepare more solution. This suggestion has been included in the Field Test Procedures for Environmental Sensor Stations.

Some personal information about the operators was also recorded. All operators were male and the average age was 49 years. The operators all had technical degrees or some college education. All operators were very familiar with computers and used the Internet both at work and home. One question asked the operators to rate themselves in math and science and a variety of responses was obtained. By observation, this perceived ability did not correlate with the level of comfort each operator had running the test. While the test procedures are based on scientific principles, they were simple enough for the operators to understand given the short training session.

CHAPTER 3
Interpretations and Appraisal

This section presents some interpretations of the laboratory and field tests, which further explain how to address issues for field testing. They are broken down by test as follows.

TEST INTERPRETATIONS

Temperature

Ambient Temperature Test. The biggest issue with the ambient temperature test is that temperature accuracy is dependent on the level of shading done before the test. For this reason, the ice fishing shelter has been recommended for use in the Field Test Procedures for Environmental Sensor Stations. While it may not seem to be necessary, other methods were tried and could not produce the same level of accuracy. The most important quality of this form of sheltering is that it protects a large area from solar radiation. Because the sun does not heat the pavement evenly (a pronounced gradient forms with respect to depth) this is important to control for temperature stability.

Ice Bath Test. This test gives similar findings to the ambient temperature test, but takes much longer to run. Because the pavement must cool to 32° F (0° C), the time required is weather dependent. Warm to hot days will require the operator to stir much longer than cool days. The test also changes the temperature of the pavement sensor that is less desirable in case the operator wants to do additional ambient temperature testing.

Surface State

Frost Test. While frost could not be intentionally formed in either the laboratory or field, one possible solution was discovered in field testing. If the operator places dry ice on the sensor for about ten minutes to lower the pavement temperature, the pavement will cool. When the dry ice is removed, frost may form on the pavement sensor surface over the next ten minutes. This method was tried once on Sensor B while field testing in Nevada. The RPU reported a "frosty" condition. However, because dry ice has been removed from the Field Test Procedures for Environmental Sensor Stations due to many manufacturers' concerns, this method is not acceptable to recommend in the Field Test Procedures for Environmental Sensor Stations. If individual agencies are interested in this method of producing frost, it is left to their own discretion to put dry ice on the sensor.

Dry/Wet/Ice Test. One of the major concerns for this test is the amount of time it takes for a sensor to report a new condition. Based on the variation in response time found in the field tests, each surface state should be given from two to eight minutes to respond to a new surface state condition. Because not all manufacturers' sensors were tested, an additional two minutes has been added to the time allowed for the surface state to change. The ten minute update time has been noted in the Field Test Procedures for Environmental Sensor Stations.

Freezing Point

Passive Sensor Test. While the passive sensor test procedures did not find accurate results at high concentrations, the tests did reveal that the sensors almost always reflect a freezing point depression after the sodium chloride solutions were applied to them. A tolerance of 3.0° F (1.6° C) is specified in the Field Test Procedures for Environmental Sensor Stations. If the sensor is not meeting this requirement, it may be sufficient for the operator to use an alternative criterion, such as whether the sensor reports a reasonable change in freezing point. This will be left up to the individual agency to deviate from the test protocols.

One problem, which may also have caused some inconsistency, is that the solution ran from the sensor site because of the crown of the roadway. A paper towel was laid on the pavement before the sensor was sprayed and the paper towel absorbed the solution. This made it more difficult to measure the thickness of the film. The use of the paper towel was a necessary step in proceeding with the field testing and the method was effective. The method has been added to the Field Test Procedures for Environmental Sensor Stations as a workaround if the solution will not stay on the pavement sensor. Despite the utility of the paper towel, some vendors commented that the method could create errors in testing. Other suggested methods were not feasible because they would leave residue that would create future errors in sensor data.

From the results of the data, it was decided that a low concentration would be the best for testing a wide variety of pavement sensors. A concentration of 4 percent and 15 percent was chosen to be included in the Field Test Procedures for Environmental Sensor Stations because it will give accuracy recommendations at low and high concentrations.

Active Sensor Test. No major issues were found with the active sensor test, though it is necessary to have specific temperature conditions because the sensor uses a thermal process instead of an electrical process.

IMPLEMENTATION RECOMMENDATIONS

The following implementation scenario is envisioned as a typical scenario. Different agencies may have policies that would necessitate the testing be done in a different manner. The test procedures are flexible and allow for some different testing conditions.

Who should be involved? The first person who will be involved in implementing these procedures will typically be the RWIS Coordinator or someone with a similar position. This person will identify sites and personnel for testing. It is recommended that a minimum of two operators work in a team to run the procedures. The procedures can be run by one person, though.

Also, because a lane closure is necessary for the testing procedures, advance scheduling will be needed. Testing will often need to be scheduled based on lane closure restrictions—especially in metropolitan areas.

When. For most cases, the best time to run the procedures is fall in preparation for the coming winter maintenance season. The warmer weather will make the testing more comfortable for the technicians who will be able to work more efficiently. In most cases, the warmer weather will still allow testing to be accomplished, although some procedures with some sensors require cold weather (such as the freezing point and ice surface state test).

Time Commitment. The test procedures have been developed to require a minimum amount of time for training and testing while still remaining accurate and thorough. One half-day of training is required to learn the test procedures. A full day should be allotted for each sensor site. Testing at each site will take an approximately one half-day to run the suite of tests at a moderate pace. Additional time is allotted for travel time and retesting if necessary.

It is not necessary for all sensors to be tested for these test methods to be used properly. It will often only be necessary for sensors that are suspected deficient in certain or all parameters to be tested. For example, if the temperature at one site is suspect, but all other parameters look accurate, the RWIS Coordinator may decide to only run the temperature test. If the procedures are used for acceptance tests, the entire suite will most likely be run.

Cost. Compared to the benefits of conducting this testing, the initial setup costs are minimal. The test equipment costs under $1,500, though some optional communications equipment may be required depending on the agency. Another major cost is the portable computer, though many agencies will have computers available for temporary use or already procured for ESS maintenance. The largest costs for the test equipment are the two thermometers and thermistors ($920) and the shelter tent ($350). Other substantial costs are the PVC pipe to hold the ice bath ($80, though a section of a 5-gallon bucket could be used for the same function) and the power inverter ($30 to $100 depending on the power needed). The combined cost of other miscellaneous supplies should be under $200.

For the field testing conducted in the states, the total cost of test equipment excluding the infrared thermometers was $1,470 including serial data radios for wireless communications.

The Aurora Consortium is currently considering funding test kits for Aurora members. Each state DOT would have the same basic kits and would able to modify the kit depending on their particular testing needs.

Barriers. Despite the ease of the tests, there are some barriers that the research project has identified through testing and interviews with sensor manufacturers and state agency personnel. They are presented here to further explain the concerns and offer some solutions for surmounting the barriers.

Some manufacturers may require their technicians to be on hand for the testing. Although most state DOTs own their ESS equipment, they may not necessarily know how to access the sensor data locally. Especially in cases where the sensor maintenance is contracted, it may be difficult to obtain access to the RPU. Some agreement could be made to "warranty" the sensor at the time of procurement with a clause for how the sensor will be tested. The agency could specify that one or more of the tests developed in this research project be used to prove that the sensors are in compliance.

Another barrier is configuring the ESS system to output data every two minutes. Although none of the state visits revealed that this was difficult to do, adequate preparation was done for these tests to assure that it would be possible. Some setups can be configured to automatically poll the RPU every two minutes while other setups required the operator to manually poll the sensor. In the case of the Sensor B, the RPU was configured to store the reading every two minutes and the operator needed to recall the stored data.

CONCLUSION

The implementation recommendations presented here show many of the concerns agencies may face when considering using these guidelines. As seen in the state visits, there are many ways to solve these concerns and the ESS maintenance personnel are usually the best experts for solving the technical concerns.

CHAPTER 4
Conclusions and Suggested Research

This research project originally included developing methods for the field *calibration* of pavement sensors. However, early in the research and during discussions with pavement sensor manufacturers, it was determined that pavement sensor calibration is a factory setting or not available. Therefore, it was decided that pavement sensor calibration could not be applied to a field testing operation. Instead, this research has focused on developing field *test* methods.

Based on a survey of DOT RWIS experts, it was found that for the testing methods to be implemented, the testing procedures should take from one to two hours per site to complete, and the training should take about one day. Through field testing, the procedures validated in the laboratory testing have been refined to meet these expectations. While the tests allow for more thorough testing through repeated tests and more data to be taken with each test, the four test procedures may be run quickly and efficiently to evaluate ESS sensor accuracy.

A critical component of this research project has been the detailed testing of the various methodologies that have been developed for testing ESS pavement sensors. While the laboratory setting provided a controlled environment in which to experiment with different test techniques and refine these methodologies, the field testing showed which tests could withstand operator variation. Some of the tests were modified to allow for variation and the results from this investigation have provided a sound basis for publishing field test methodologies. Based on these findings, the following major conclusions and recommendations are offered for testing pavement sensors:

- Pavement sensors and thermistor baselines are extremely sensitive to solar radiation, but can give precise results when shaded properly.
- As found in the laboratory testing, active sensors are better at determining the freezing point of a solution on the road, but passive sensors can still be tested using the procedures developed in this project.
- Pavement sensors can adequately monitor wet/dry/ice surface state conditions, but the sensor must be thoroughly dried (for example, with a heat gun) before the sensor will read a dry condition.
- Because it is difficult to simulate frost in a laboratory and field environment, it is not practical to test pavement sensors for frost measurement compliance.
- In order to serve the RWIS community, atmospheric guidelines have also been integrated into the Field Test Procedures for Environmental Sensor Stations so RWIS maintenance personnel can have a single document to rely on for ESS maintenance.

A major effort was made to encourage all types of RWIS stakeholders to participate in developing the testing protocols. The end users, such as the state DOTs, and the sensor manufacturers were included in this effort. Both the draft testing procedures and data were shared with the vendors to allow them to respond to the tests. The goal of these efforts is for the guidelines to be universally accepted.

Based on feedback from the states, many agencies would like to implement these procedures as a quality control measure. One way of accomplishing this would be to reference the test procedures in RWIS procurement efforts. This would create a mechanism for objectively measuring ESS sensor performance on an ongoing basis after the sensors have been installed. The manner in which this study's findings will be used is left up to the individual agencies; it is hoped they will become an important tool in promoting ESS sensor accuracy in the future.

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APPENDIX B
STAKEHOLDER SURVEY

Thank you for participating in the NCHRP R/WIS user survey. This survey consists of three parts: I) General calibration questions; II) Sensor-specific information – pavement; and III) Sensor-specific questions – atmospheric. In some cases, information such as copies of procedures or manuals may be requested. These items may be provided at your discretion and convenience. If they cannot be provided, please complete and return the remainder of the survey.

If there is any other information that you believe would be useful in conjunction with the survey, please include as many additional sheets as appropriate.

Part I: General calibration questions:

1. If standardized procedures that increase the reliability and usefulness of RWIS sensor data were available, would you be willing to implement them?

   _____ Yes _____ No

2. If standardized procedures provided consistent, useful results, but required more person-hours to complete, what is the maximum additional time commitment that would be acceptable? Time is expressed in terms of hours to calibrate one RWIS station, which may include multiple sensors.

   _____ Less than 1 hour _____ 1 to 2 hours _____ 2 to 3 hours _____ 3 to 4 hours

3. If standardized procedures improved sensor usefulness but required additional staff training to implement, what is the maximum investment in additional training that would be acceptable?

   _____ Less than ½ day _____ ½ to 1 day _____ 1 to 2 days _____ More than 2 days

Part II: Pavement sensor-specific questions

Please answer the following questions for each type of pavement sensor that you have deployed. If a single pavement sensor device can collect multiple types of data, please note this on the form.

A separate page is included for each pavement sensor type, indicated by a header at the top of the page. Please complete the appropriate page for each sensor you use.

Sensor Type: Surface Temp
Detailed Sensor Information

1. Sensor Manufacturer: ______________________________

2. Sensor Model: ______________________________

3. Approximate first date of deployment for this sensor model: ______________

4. Is this sensor calibrated by:

   _____ Public Employee ______ Private Contractor

5. What is the manufacturer-reported or observed accuracy for this sensor: __________

6. Do you have a specific accuracy requirement for this sensor? _____ Yes _____ No

   If yes, what is the accuracy value needed ______________________

7. Do you have a standard procedure for verifying this accuracy? _____ Yes _____ No

   - If yes, do you conduct an initial test? _____ Yes _____ No
     (Please describe test, including number of person-hours)

     ____
     ____
     ____

   - Do you test the sensor periodically? _____ Yes _____ No
     (Please describe test and frequency of test, including number of person-hours)

     ____
     ____
     ____

8. Do you have a standard procedure for calibrating this sensor? _____ Yes _____ No

   - Do you calibrate the sensor periodically? _____ Yes _____ No
     (Please describe calibration procedure and frequency of calibration, including number of person-hours)

     ____
     ____
     ____

9. Do you have a written procedure or manual for sensor calibration, testing and maintenance? ______ Yes ______No

   - If so, please provide a copy of the relevant manual section or if this is not feasible, please indicate where copies may be obtained in the Comments section of the survey.

10. Are you confident that the procedures used for calibration provide the accuracy required in question 6? ______ Yes ______No

Sensor Type: Sub-Surface Temp
Detailed Sensor Information

1. Sensor Manufacturer: ____

2. Sensor Model: ____

3. Approximate first date of deployment for this sensor model: ____________________

4. Is this sensor calibrated by:

   _____ Public Employee ______ Private Contractor

5. What is the manufacturer-reported or observed accuracy for this sensor: ____________

6. Do you have a specific accuracy requirement for this sensor? _____ Yes _____ No

   If yes, what is the accuracy value needed ______________________________

7. Do you have a standard procedure for verifying this accuracy? _____ Yes _____ No

   - If yes, do you conduct an initial test? _____ Yes _____ No
     (Please describe test, including number of person-hours)
     ____
     ____
     ____
   - Do you test the sensor periodically? _____ Yes _____ No
     (Please describe test and frequency of test, including number of person-hours)
     ____
     ____
     ____

8. Do you have a standard procedure for calibrating this sensor? _____ Yes _____ No

   - Do you calibrate the sensor periodically? _____ Yes _____ No
     (Please describe calibration procedure and frequency of calibration, including number of person-hours)
     ____
     ____
     ____

9. Do you have a written procedure or manual for sensor calibration, testing and maintenance? _____ Yes _____ No

   - If so, please provide a copy of the relevant manual section or if this is not feasible, please indicate where copies may be obtained in the Comments section of the survey.

10. Are you confident that the procedures used for calibration provide the accuracy required in question 6? _____ Yes _____ No

Sensor Type: Wet/Dry
Detailed Sensor Information

1. Sensor Manufacturer: ____

2. Sensor Model: ____

3. Approximate first date of deployment for this sensor model: ___________________

4. Is this sensor calibrated by:

   _____ Public Employee ______ Private Contractor

5. What is the manufacturer-reported or observed accuracy for this sensor: ____________

6. Do you have a specific accuracy requirement for this sensor? _____ Yes _____ No

   If yes, what is the accuracy value needed ______________________________

7. Do you have a standard procedure for verifying this accuracy? _____ Yes _____ No

   - If yes, do you conduct an initial test? _____ Yes _____ No
     (Please describe test, including number of person-hours)

     ____
     ____
     ____

   - Do you test the sensor periodically? _____ Yes _____ No
     (Please describe test and frequency of test, including number of person-hours)

     ____
     ____
     ____

8. Do you have a standard procedure for calibrating this sensor? _____ Yes _____ No

   - Do you calibrate the sensor periodically? _____ Yes _____ No

     (Please describe calibration procedure and frequency of calibration, including number of person-hours)

     ____
     ____
     ____

9. Do you have a written procedure or manual for sensor calibration, testing and maintenance? _____ Yes _____ No

   - If so, please provide a copy of the relevant manual section or if this is not feasible, please indicate where copies may be obtained in the Comments section of the survey.

10. Are you confident that the procedures used for calibration provide the accuracy required in question 6? _____ Yes _____ No

Sensor Type: Subsurface Moisture Content
Detailed Sensor Information

1. Sensor Manufacturer: ______________________________

2. Sensor Model: ______________________________

3. Approximate first date of deployment for this sensor model: ______________

4. Is this sensor calibrated by:

   _____ Public Employee   ______ Private Contractor

5. What is the manufacturer-reported or observed accuracy for this sensor: ____________

6. Do you have a specific accuracy requirement for this sensor? _____ Yes _____ No

   If yes, what is the accuracy value needed ______________________________

7. Do you have a standard procedure for verifying this accuracy? _____ Yes _____ No

   ▪ If yes, do you conduct an initial test? _____ Yes _____ No
   (Please describe test, including number of person-hours)

   ____

   ____

   ____

   ▪ Do you test the sensor periodically? _____ Yes _____ No
   (Please describe test and frequency of test, including number of person-hours)

   ____

   ____

   ____

8. Do you have a standard procedure for calibrating this sensor? _____ Yes _____ No

   ▪ Do you calibrate the sensor periodically? _____ Yes _____ No
   (Please describe calibration procedure and frequency of calibration, including number of person-hours)

   ____

   ____

   ____

9. Do you have a written procedure or manual for sensor calibration, testing and maintenance? _____ Yes _____ No

   ▪ If so, please provide a copy of the relevant manual section or if this is not feasible, please indicate where copies may be obtained in the Comments section of the survey.

10. Are you confident that the procedures used for calibration provide the accuracy required in question 6? _____ Yes _____ No

Sensor Type: Salinity
Detailed Sensor Information

1. Sensor Manufacturer: ______________________________

2. Sensor Model: ______________________________

3. Approximate first date of deployment for this sensor model: ______________

4. Is this sensor calibrated by:

   _____ Public Employee ______ Private Contractor

5. What is the manufacturer-reported or observed accuracy for this sensor: __________

6. Do you have a specific accuracy requirement for this sensor? _____ Yes _____ No

   If yes, what is the accuracy value needed ______________________________

7. Do you have a standard procedure for verifying this accuracy? _____ Yes _____ No

   - If yes, do you conduct an initial test? _____ Yes _____ No
     (Please describe test, including number of person-hours)

     ____

     ____

     ____

   - Do you test the sensor periodically? _____ Yes _____ No
     (Please describe test and frequency of test, including number of person-hours)

     ____

     ____

     ____

8. Do you have a standard procedure for calibrating this sensor? _____ Yes _____ No

   - Do you calibrate the sensor periodically? _____ Yes _____ No

     (Please describe calibration procedure and frequency of calibration, including number of person-hours)

     ____

     ____

     ____

9. Do you have a written procedure or manual for sensor calibration, testing and maintenance? _____ Yes _____ No

   - If so, please provide a copy of the relevant manual section or if this is not feasible, please indicate where copies may be obtained in the Comments section of the survey.

10. Are you confident that the procedures used for calibration provide the accuracy required in question 6? _____ Yes _____ No

Sensor Type: Freezing Point
Detailed Sensor Information

1. Sensor Manufacturer: ______________________________

2. Sensor Model: ______________________________

3. Approximate first date of deployment for this sensor model: ______________

4. Is this sensor calibrated by:

   _____ Public Employee _____ Private Contractor

5. What is the manufacturer-reported or observed accuracy for this sensor: __________

6. Do you have a specific accuracy requirement for this sensor? _____ Yes _____ No

   If yes, what is the accuracy value needed ______________________

7. Do you have a standard procedure for verifying this accuracy? _____ Yes _____ No

   - If yes, do you conduct an initial test? _____ Yes _____ No
     (Please describe test, including number of person-hours)

     ____

     ____

     ____

   - Do you test the sensor periodically? _____ Yes _____ No
     (Please describe test and frequency of test, including number of person-hours)

     ____

     ____

     ____

8. Do you have a standard procedure for calibrating this sensor? _____ Yes _____ No

   - Do you calibrate the sensor periodically? _____ Yes _____ No

     (Please describe calibration procedure and frequency of calibration, including number of person-hours)

     ____

     ____

     ____

9. Do you have a written procedure or manual for sensor calibration, testing and maintenance? _____ Yes _____ No

   - If so, please provide a copy of the relevant manual section or if this is not feasible, please indicate where copies may be obtained in the Comments section of the survey.

10. Are you confident that the procedures used for calibration provide the accuracy required in question 6? _____ Yes _____ No

Part III: Atmospheric sensor-specific questions

1. Do you have a standard procedure for calibrating any of the atmospheric sensors you use?
 _____ Yes _____ No

 - If yes, do you conduct an initial calibration? _____ Yes _____ No
 - Do you calibrate the sensor periodically? _____ Yes _____ No

2. Do you have a written procedure or manual for atmospheric sensor calibration, testing and maintenance? _____ Yes _____ No

3. In the table below, please list the types of sensors you have in use (anemometer, wind direction, hygrometer, etc.) and the manufacturer for the sensor.

Sensor Type	**Manufacturer**

ADDITIONAL COMMENTS

____
____
____
____
____
____
____
____
____
____
____
____

APPENDIX C
TABULATION OF STAKEHOLDER SUMMARY

Table C-1. Part I: General Calibration Questions

State	1		2				3			
	Yes	No	< 1hr	1-2hrs	2-3 hrs	3-4 hrs	< 1/2 day	1/2 -1 day	1 - 2days	> 2 days
No.1	**X**		**X**					**X**		
No.2	**X**				**X**					**X**
No.3	**X**					**X**			**X**	
No.4	**X**			**X**						**X**
No.5	**X**				**X**					
No.6	**X**		**X**				**X**			
No.7	**X**					**X**				**X**
No.8	**X**			**X**				**X**		
No.9	**X**			**X**	**X**			**X**		
No.10	**X**			**X**					**X**	
No.11	**X**			**X**			**X**			
No.12	**X**			**X**				**X**		
No.13	**X**		**X**					**X**		
No.14	**X**		**X**				**X**			
No.15	**X**			**X**				**X**		
No.16	**N/R**									
No.17	**X**			**X**				**X**		
No.18	**X**			**X**					**X**	
No.19	**X**			**X**					**X**	
Total	18	0	4	10	3	2	3	7	4	3

Note: N/R = Non Response

Table C-2. Part II: Questions for Surface Temperature Sensors

Question	1		2		3	4		5	6		7						8				9		10	
State	Manufacturer		Model		Date	Sensor Calibration		Accuracy	Specific requirements		Verifying accuracy		Initial test test		Periodica testing		Standard Procedures		Periodically calibrate		Written Procedures		Confidence in Procedures	
	SSI	Other	S16UG-D	Other	Year	Public	Private		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
No.1	X		X		2003		X	+/-0.3F		X		X	S/C		S/C			X	S/C			X		X
No.2	X		X		1997		X	+/-2 F		X		X	N/R		X*			X		X*		X		X
No.3	X		X		1998		X	60-176F		X	X		X*		X*		X		X*		X		X	
No.4	X		X		1990	X		+/-0.36F	X			X		X	X			X		X		X		X
No.5	X		X		1997		X	+/-0.36F		X		X		N/R	X			X	N/R			X	N/R	
No.6	X		X		1992		X	+/-0.36F		X		X		N/R*		X		X		X*		X		X
No.7	X		X		1995		X	**+/-0.36F**	X*		X		X		X*		X		X*		X		X	
No.8	X	NuMetrics, Quixote	X	G2 E-Type	1994, 2003 1992		X	+/- 2 D	X		X		X		X		S/C		S/C			X		X
No.9	X		X		**N/R**		X	**N/R**	N/R			X	N/R		X*		X		X*			X	?	
No.10	X		X		2000		X	**S/C**	N/R		X		X		X		X		X		X		X	
No.11	X		X&"E"		1989/1995		X	**N/R**	X*			X	N/R		N/R		X		X			X		X
No.12	X		X		**N/R**	X		**+/-0.36F**		X			S/C		X		X		X		N/R			X
No.13	X		X		**2000**		X	**UNKNOWN**		X		X		X		X		X		X		X	N/R	
No.14	X		**Varies**		**N/R**	N/R		**Do not know**		X		X	N/R			X		X		X		X		X
No.15	X		X		**1995**		X	**+/-0.36F**	X*			X	N/R			X		X	N/R			X		X
No.16	X		X		**1994**		?	**+/-0.36F**		X		X		X		X	N/R			X		X	N/R	
No.17	X		X		**1995**	X		**UNKNOWN**		X		X	N/R			X		X		X		X		X
No.18		**Vaisala**		N/R	**2001**		X	**+/- 1 D**		X	X		X*			X		X	X*			X		X
No.19	X		X		**1996**	X	X	**+/-0.36F**		X		X		X*		X	X		X*			X		X

Note: N/R = Non Response

Table C-3. Part II: Questions for Sub-Surface Temperature Sensors

State	Manufacturer		Model		Date	Sensor Calibration		Accuracy	Specific accuracy requirements		Verifying this accuracy		Initial test test		Periodically testing		Standard Procedures		Periodically calibrate sensor		Written Procedures		Confidence in Procedures	
	SSI	Other	S16UG-D	Other	Year	Public	Private		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
No.1	X		X		2003		X	+/-0.36F		X		X	N/R		N/R		S/C		S/C			X		X
No.2	X		N/R		1989		X	Unknown		X		X	N/R			N/R*		X		X		X		X
No.3	X		X		1995		X	-40to 176F		X		X	N/R		X*			X		X*		X	N/R	
No.4	X		X		1990	X		+/-0.36F	X			X		X		X		X		X		X		X
No.5	X		X		1997		X	+/-0.36F		X		X	N/R		X			X	X			X	N/R	
No.6	X		X		1992		X	+/-0.36F		X		X		N/R		X*		X		N/R		X	X	
No.7	X		X		N/R		X	+/-0.36F		X	X		X*		X*			X		X	X		X	
No.8	X		X		1992		X	N/R		X	N/R		N/A			X		X		X		X		X
No.9		N/R		N/R	N/R		X	N/R		N/R		X		N/A	X		X		X*			X	?	
No.10	X		X		1990		X	S/C	X		X		X		X		X		X		X		X	
No.11	X		N/R		1989		X	N/R	X*			X		N/R		N/R		X		X		X		X
No.12	X		X		N/R	X		+/-0.36F		X	N/R		N/R		N/R		N/R		N/R		N/R			X
No.13	X		X		2000		X	Unknown		X		X		X		X		X		X		X	N/R	
No.14	Same as Surface Temperature																							
No.15	X		X		1995		X	+/-0.36F	X*			X	N/R			X		X	N/R			X		X
No.16	X		X		1992		?	+/-0.36F		X		X		X		X		X		X		X	N/R	
No.17	X		X		1995	X		+/-0.36F		X		X	N/R			X		X		X		X		X
No.18		Vaisala		N/R	2001		X	+/- 1D		X		X	N/R			X		X	X*			X		X
No.19	X		X		1991	N/R		+/-0.36F		X		X		X	X*			X		X		X		X

Note: N/R = Non Response

Table C-4. Part II: Questions for Sub-Surface Temperature Sensors

Question	1		2		3	4		5	6		7						8				9		10	
State	Manufacturer		Model		Date	Sensor Calibration		Accuracy	Specific requirements		Verifying this accuracy		Initial test test		Periodically testing		Standard Procedures		Periodically calibrate		Written Procedures		Confidence in Procedures	
	SSI	Other	S16UG-D	Other	Year	Public	Private		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
No.1	Did not understand question. Indicate precipitation Sensor																							
No.2	Did not understand question. Indicate precipitation Sensor																							
No.3	X		X		1998		X	N/R		X		X		X*	X*		X			X*	X		X	
No.4	X		X		1990	X		N/R		X	X			X	X		X		X			X	X	
No.5		SCTT		ORG-715	1997		X	?		X		X		N/R	X			X	X			X	N/R	
No.6	X		X		1992		X	N/R		X		X		N/R		X		X		N/R		X	X	
No.7	X		X		1995		X	NONE		X	X		X*		X*		X		X		X		X	
No.8	Same as FP2000																							
No.9		THIES			N/R		X	N/R		X		X	N/R		X		X		X*			X	?	
No.10	X		X		2000		X	S/C	X		X		X		X		X		X		X		X	
No.11	X		X&E		1989/1995		X			X		X		X		X	X		X			X		X
No.12	Same as FP2000																							
No.13	X		X		2000		X	Unknown		X		X		X		X		X		X		X	N/R	
No.14	Same as Surface Temp																							
No.15	N/R																							
No.16	X		X		1994	X		N/R		X	X			X	X		X			X	X		X	
No.17	X		X		1995	X		Unknown		X		X	N/R			X		X	N/R			X		X
No.18		vaisala		N/R	2001		X	N/R		X		X	N/R			X	X		N/R			X		X
No. 19	N/R		N/R		N/R	N/R		N/R	N/R		N/R		N/R		N/R		N/R		N/R		N/R		N/R	

N/R = Non Response

Table C-5. Part II: Questions for Wet/Dry Sensors

Question	1		2		3	4		5	6		7						8				9		10	
State	Manufacturer		Model		Date	Sensor Calibration		Accuracy	Specific requirements		Verifying this accuracy		Initial test test		Periodically testing		Standard Procedures		Periodically calibrate		Written Procedures		Confidence in Procedures	
	SSI	Other	S16UG-D	Other	Year	Public	Private		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
No.1	Did not understand question. Indicate precipitation Sensor																							
No.2	Did not understand question. Indicate precipitation Sensor																							
No.3	X		X		1998		X	N/R		X		X		X*	X*		X			X*	X		X	
No.4	X		X		1990	X		N/R		X	X			X	X		X		X			X	X	
No.5		SCTT		ORG-715	1997		X	?		X		X		N/R	X			X	X			X	N/R	
No.6	X		X		1992		X	N/R		X		X		N/R		X		X		N/R		X	X	
No.7	X		X		1995		X	NONE		X	X		X*		X*		X		X		X		X	
No.8	Same as FP2000																							
No.9		THIES			N/R		X	N/R		X		X	N/R		X		X		X*			X	?	
No.10	X		X		2000		X	S/C	X		X		X		X		X		X		X		X	
No.11	X		X&E		1989/1995		X			X		X		X		X	X		X			X		X
No.12	Same as FP2000																							
No.13	X		X		2000		X	Unknown		X		X		X		X		X		X		X	N/R	
No.14	Same as Surface Temp																							
No.15	N/R																							
No.16	X		X		1994	X		N/R		X	X			X	X		X			X	X		X	
No.17	X		X		1995	X		Unknown		X		X	N/R			X		X	N/R			X		X
No.18		vaisala		N/R	2001		X	N/R		X		X	N/R			X	X		N/R			X		X
No. 19	N/R		N/R		N/R	N/R		N/R	N/R		N/R		N/R		N/R		N/R		N/R		N/R		N/R	

Table C-6. Part II: Questions for Moisture Content Sensors

Question	1		2		3	4		5	6		7						8				9		10	
State	Manufacturer		Model		Date	Sensor Calibration		Accuracy	Specific requirements		Verifying this accuracy		Initial test test		Periodically testing		Standard Procedures		Periodically calibrate		Written Procedures		Confidence in Procedures	
	SSI	Other	S16UG-D	Other	Year	Public	Private		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
No.1	**N/A**																							
No.2	**N/A**																							
No.3	**N/A**																							
No.4	Environmental Sensors Inc.			TDR Moisture Point*	2001	**X**		Unknown		X		X		X		X		X		X		X		X
No.5	**N/A**																							
No.6	**N/A**																							
No.7	**N/A**																							
No.8	Same as Sub-Surface																							
No.9	**N/R**																							
No.10	**N/A**																							
No.11	**N/A**																							
No.12	**N/R**																							
No.13	**N/A**																							
No.14	Same as Sub-Surface																							
No.15	**N/A**																							
No.16	**N/A**																							
No.17	**N/A**																							
No.18		**vaisala**		**N/R**	**2001**		**X**	**N/R**		**X**		**X**	**N/R**			**X**	**X**		**N/R**			**X**		**X**
No.19	**N/R**																							

Note= * This sensor is used as a frost probe and not moisture content
N/A = Not Applicable
N/R = Non Response

Table C-7. Part II: Questions for Salinity Sensors

Question	1		2		3	4		5	6		7						8				9		10	
State	Manufacturer		Model		Date	Sensor Calibration		Accuracy	Specific requirements		Verifying this accuracy		Initial test test		Periodically testing		Standard Procedures		Periodically calibrate		Written Procedures		Confidence in Procedures	
	SSI	Other	S16UG-D	Other	Year	Public	Private		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
No.1	**X**		**X**		**2003**	**N/R**		**N/R**	**N/R**		**N/R**		**N/R**		**N/R**		**N/R**		**X***		**N/R**		**N/R**	
No.2	**X**		**X**		**1996**		**X**	**Unknown**		**X**		**X**		**X**	**X**			**X**		**X**		**X**		**X**
No.3	**See WET/DRY Section**																							
No.4	**X**		**X**		**1990**	**X**		**Unknown**		**X**	**X**			**X**	**X**			**X**		**X**		**X**		**X**
No.5	**X**		**X**		**1997**		**X**	**?**		**X**		**X**	**N/R**		**X**			**X**	**X**			**X**	**N/R**	
No.6	**X**		**X**		**1992**		**X**	**?**		**X**		**X**	**N/R**			**X**		**X**		**N/R**		**X**	**X**	
No.7	**X**		**X**		**1995**		**X**	**NONE**		**X**		**X**	**N/R**			**X**		**X**		**X**		**X**		**X**
No.8	Same As FP2000																							
No.9	**N/R**																							
No.10	**X**		**X**		**2000**		**X**	**S/C**	**X**		**X**		**X**		**X**		**X**		**X**		**X**		**X**	
No.11	**X**		**X**		**1995**		**X**	**N/R**		**X**		**X**		**N/R**		**N/R**	**X**		**X**			**X**		**X**
No.12	**N/R**																							
No.13	**X**		**X**		**2000**		**X**	**Unknown**		**X**		**X**		**X**		**X**		**X**		**X**		**X**	**N/R**	
No.14	**Same as Surface Temperature**																							
No.15	**X**		**X**		**1995**		**X**	**Unknown**		**X**		**X**	**N/R**			**X**		**X**	**N/R**			**X**		**X**
No.16	**X**		**X**		**1994**		**?**	**N/R**		**X**	**X**		**X***			**X**	**X**			**X**	**X**		**X**	
No.17	**X**		**X**		**1995**	**X**		**Unknown**		**X**		**X**	**N/R**			**X**		**X**		**X**		**X**		**X**
No.18		**vaisala**			**N/R**		**X**	**N/R**		**X**		**X**	**N/R**			**X**	**X**		**N/R**			**X**		**X**
No.19	**N/R**		**N/R**		**N/R**	**N/R**		**N/R**	**N/R**		**N/R**		**N/R**		**N/R**		**N/R**		**N/R**		**N/R**		**N/R**	

Note: N/R = Non Response

Table C-8. Part II: Questions for Freezing Point Sensors

Question	1		2		3	4		5	6		7						8				9		10	
State	Manufacturer		Model		Date	Sensor Calibration		Accuracy	Specific requirements		Verifying this accuracy		Initial test test		Periodically testing		Standard Procedures		Periodically calibrate		Written Procedures		Confidence in Procedures	
	SSI	Other	S16UG-D	Other	Year	Public	Private		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
No.1	**X**		**X**		**2003**	**N/R**		**N/R**	**N/R**		**N/R**		**N/R**		**N/R**		**N/R**		**X***		**N/R**		**N/R**	
No.2	**X**		**X**		**1996**		**X**	**Unknown**		**X**		**X**		**N/R**		**X***		**X**		**X**		**X**		**X**
No.3	**See WET/DRY Section**																							
No.4	**X**		**X**		**1990**	**X**		**Unknown**	**X**		**X**			**X**	**X**			**X**		**X**		**X**		**X**
No.5	**X**		**X**		**1997**		**X**	**?**		**X**		**X**	**N/R**		**X**			**X**	**X**			**X**	**N/R**	
No.6	**X**		**X**		**1992**		**X**	**+/-0.36F**		**X**		**X**	**N/R**			**X**		**X**		**N/R**		**X**	**X**	
No.7	**X**		**X**		**1995**		**X**	**See attachment**	**N/R**		**X**			**X**	**X**		**X**		**X**		**X**		**X**	
No.8	**N/R**																							
No.9	**N/R**																							
No.10	**X**		**X**		**2000**		**X**	**S/C**	**X**		**X**		**X**		**X**		**X**		**X**		**X**		**X**	
No.11	**X**		**X**		**1995**		**X**	**N/R**		**X**		**X**		**X**		**X**	**X**		**X**			**X**		**X**
No.12	**N/R**																							
No.13	**X**		**X**		**2000**		**X**	**Unknown**		**X**		**X**		**X**		**X**		**X**		**X**		**X**	**N/R**	
No.14	**Same as Surface Temperature**																							
No.15	**N/R**																							
No.16	**X**		**X**		**1994**	**N/R**		**+/-0.36F**		**X**		**X**		**X**		**X**		**X**		**X**		**X**	**N/R**	
No.17	**X**		**X**		**1995**	**X**		**Unknown**		**X**		**X**	**N/R**			**X**		**X**		**X**		**X**		**X**
No.18		**vaisala**		**N/R**	**2001**		**X**	**N/R**		**X**	**N/R**			**X**		**X**	**X***		**N/R**			**X**		**X**
No.19	**N/R**		**N/R**		**N/R**	**N/R**		**N/R**	**N/R**		**N/R**		**N/R**		**N/R**		**N/R**		**N/R**		**N/R**		**N/R**	

Note: N/R = Non Response

Table C-9. Part III: Questions for Atmospheric Sensors

State	**Procedures for Calibration**		**Conduct initial Calibration**		**Periodically Calibration**		**Written Procedures for Calibration**		**Manufacture of Atmospheric Sensors**						
	Yes	No	Yes	No	Yes	No	Yes	No	Wind	Air Temp	Relative Humidty	Precipitation	Visibilty	Pressure	Radiation
No.1		**X**	**N/R**		**N/R**			**X**	RM Young						
No.2		**X**		**X**	**X**			**X**	RM Young	Thies	Thies		Belfort		
No.3	**X**		**X**		**X**		**X**		RM Young	Thies	Thies	WIVIS	WIVIS	Met One Instruments Model 091	Handar Model 410AN
No.4	**X**			**X**	**X**		**X**		RM Young	Thies	Thies	WIVIS/OWI/PRICE	WIVIS		
No.5		**X**		**X**	**X**			**X**	RM Young	Thies	Thies	SCTI-ORG-715-DA			
No.6		**X**		**N/R**		**X**		**X**	RM Young	Thies	Thies	PRICE	Belfort		
No.7	**X**			**X**	**X**		**X**		RM Young	Thies	Thies	OWI	Belfort		
No.8	**X**		**X**		**X**			**X**	RM Young	Thies	Thies	WIVIS	VAISALA		
No.9		**X**		**N/R**		**N/R**		**X**	RM Young	Thies	Thies	WIVIS	WIVIS		
No.10	**X**		**X**		**X**		**X**		RM Young	Thies	Thies	WIVIS	WIVIS		
No.11	**X**			**X**	**X**			**X**	RM Young	Thies	Thies	Price	WIVIS		
No.12	**X**			**X**	**X**		**X**		RM Young	Thies	Thies	OWI	Belfort		
No.13		**X**	**N/R**		**N/R**			**X**	RM Young	Thies	Thies	Price			
No.14		**X**	**N/R**			**X**		**X**	RM Young	Thies	Thies				
No.15		**X**	**N/R**		**N/R**			**X**	RM Young	Thies	Thies				
No.16	**X**		**X**		**X**		**X**			Thies	Thies				
No.17		**X**	**N/R**		**N/R**			**X**	RM Young	Thies	Thies	Price			
No.18		**X**	**N/R**		**X**			**X**	**N/R**	**N/R**					
No.19	**N/R**		**N/R**		**N/R**		**N/R**		**N/R**	**N/R**	**N/R**	**N/R**	**N/R**		

Note: N/R = Non Response

APPENDIX D
TEST SELECTION MATRIX DEVELOPMENT

Calibration Matrix

The following matrix (Table E-1) presents a range of options for calibration for each type of sensor. Each procedure will have a series of attributes associated with it that will allow it to be compared with the issues from the survey summarized above.

Table D-1. Calibration Matrix

Sensor Parameter	Sensor Type	Calibration Method	Performance Index or Estimated Effectiveness* (calculated from data in Table 2)	Estimated Effectiveness (Weighted)
Pavement Surface Temperature	Ambient Pavement Temperature (Dry) (Below 50º F)	A-1 Hand held Radiometer A-2 Contact with Thermistor A-3 Database Screening	10+6+9+3+4= 32 6+10+8+10+9= 42 0+5+1+1+= 8	0.25*10+0.20*6+0.1*9+0.3*3+0.15*4= 6.10 0.25*6+0.2*10+0.1*8+0.3*10+0.15*9= 8.65 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55
	Ambient Pavement Temperature (Wet) (Below 50º F)	B-1 Hand held Radiometer B-2 Water Bath with Thermistor B-3 Spray with Thermistor & paper towel B-4 Database Screening	10+6+9+3+4= 32 4+9+8+10+9= 40 4+10+8+10+9= 41 0+5+1+1+1= 8	0.25*10+0.2*6+0.1*9+0.3*3+0.15*4= 6.10 0.25*4+0.2*9+0.1*8+0.3*10+0.15*9= 6.76 0.25*4+0.2*10+0.1*8+0.3*10+0.15*9= 8.15 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55
	Pavement Temperature at 32º F (Freezing)	C-1 Ice bath with radiometer C-2. Ice bath with Thermistor C-3 Database screening	10+6+9+3+4= 32 4+9+8+10+9= 40 0+5+1+1+1= 8	0.25*10+0.2*6+0.1*9+0.3*3+0.15*4= 6.10 0.25*4+0.2*9+0.1*8+0.3*10+0.15*9= 7.95 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55

	Pavement Temperature Below 32º F (Dry Condition) (Forced)	D-1 Dry ice with radiometer D-2. Dry ice with Thermistor D-3. Database Screening	8+5+9+3+4= 29 3+9+8+10+10= 40 0+5+1+1+1= 8	0.25*8+0.2*5+0.1*9+0.3*3+0.15*4= 5.40 0.25*3+0.2*9+0.1*8+0.3*10+0.15*10= 7.85 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55
	Pavement Temperature at 32º F (Wet Condition) (Forced)	E-1 Salt brine bath with radiometer E-2 Salt brine bath with thermistor	8+5+9+3+6= 31 6+9+8+10+10= 43	0.25*8+0.2*5+0.1*9+0.3*3+0.15*6= 5.70 0.25*6+0.2*9+0.1*8+0.3*10+0.15*10= 8.60
	Ambient Pavement Temperature Below 32º F	F-1 Hand held radiometer F-2 Contact with Thermistor F-3. Database screening	10+6+9+3+4= 32 6+10+8+10+9= 43 0+5+1+1+1= 8	0.25*10+0.2*6+0.1*9+0.3*3+0.15*4= 6.10 0.25*6+0.2*10+0.1*8+0.3*10+0.15*9= 8.65 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55
Pavement Condition	Dry Condition	G-1 Visual before, cleaning G-2. Visual, after cleaning G-3. Database screening	10+10+10+10+0= 40 10+10+10+10+0= 40 0+5+1+1+1= 8	0.25*10+0.2*10+0.1*10+0.3*10+0.15*0= 8.50 0.25*10+0.2*10+0.1*10+0.3*10+0.15*0= 8.50 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55
	Wet Condition	H-1 Visual – water H-2 Visual after cleaning H-3 Using a spray H-4 Ponding over sensor	10+10+10+10+0= 40 10+10+10+10+0= 40 8+9+10+9+0= 36 7+8+10+8+0= 33	0.25*10+0.2*10+0.1*10+0.3*10+0.15*0= 8.50 0.25*10+0.2*10+0.1*10+0.3*10+0.15*0= 8.50 0.25*8+0.2*9+0.1*10+0.3*9+0.15*0= 7.50 0.25*7+0.2*8+0.1*10+0.3*8+0.15*0= 6.75
	Freezing Conditions	I-1 Visual – dry I-2 Visual after cleaning I-3 Using a spray I-4 Ponding over sensor I-5 Database screening	10+10+10+10+0= 40 10+10+10+10+0= 40 6+9+9+9+0= 33 4+7+9+9+0= 29 0+5+1+1+0= 7	0.25*10+0.2*10+0.1*10+0.3*10+0.15*0= 8.50 0.25*10+0.2*10+0.1*10+0.3*10+0.15*0= 8.50 0.25*6+0.2*9+0.1*9+0.3*9+0.15*0= 6.90 0.25*4+0.2*7+0.1*9+0.3*9+0.15*0= 6.00 0.25*0+0.2*5+0.1*1+0.3*1+0.15*0= 1.55
	Frost	J-1 Visual – Frost J-2 Database screening	10+10+10+10+0= 40 0+5+1+1+0= 7	0.25*10+0.2*10+0.1*10+0.3*10+0.15*0= 8.50 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55

Chemical Concentration/ Freezing Point	Salt Brine (4, 10, 15, 20% & saturation Concentrations)	K-1 Spraying solution K-2 Pouring solution	4+10+8+6+5=33 3+10+8+4+5= 30	0.25*4+0.2*10+0.1*8+0.3*6+0.15*5= 6.35 0.25*3+0.2*10+0.1*8+0.3*4+0.15*5= 5.50
	Magnesium Chloride (4, 10,15, 20% & saturation Concentrations)	L-1 Spraying solution L-2 Pouring solution	4+10+8+6+5+= 33 3+10+8+4+5= 30	0.25*4+0.2*10+0.1*8+0.3*4+0.15*5= 6.35 0.25*3+0.2*10+0.1*8+0.3*4+0.15*5= 5.50
Surface State Ice Depth	No sensor identified	M-1 no method identified		
Sub-surface temperature	Above 32º F	N-1 Independent probe N-2 Database N-Fixed Resistance	1+1+9+5+5= 21 0+5+1+1+1= 8 9+10+9+8+7= 43	0.25*1+0.2*1+0.1*9+0.3*5+0.15*5= 3.60 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55 0.25*9+0.2*10+0.1*9+0.3*8+0.15*7= 8.60
	Transition to Frozen	O-1 Independent probe O-2 Database O-Fixed Resistance	1+1+9+5+5= 21 0+5+1+1+1= 8 9+10+9+8+7= 43	0.25*1+0.2*1+0.1*9+0.3*5+0.15*5= 3.60 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55 0.25*9+0.2*10+0.1*9+0.3*8+0.15*7= 8.60
	Below 32º F	P-1 Independent probe P-2 Database P-3 Fixed Resistance	1+1+9+5+5= 21 0+5+1+1+1= 8 9+10+9+8+7= 43	0.25*1+0.2*1+0.1*9+0.3*5+0.15*5= 3.60 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55 0.25*9+0.2*10+0.1*9+0.3*8+0.15*7= 8.6
Sub-surface Moisture	Above 32º F	Q-1 Independent probe Q-2 Database Q-3 Sampling and laboratory testing	9+6+9+5+5= 34 0+5+1+1+1= 8 2+1+9+8+7= 27	0.25*9+0.2*6+0.1*9+0.3*5+0.15*5= 6.60 0.25*0+0.2*5+0.1*1+0.3*1+0.15*1= 1.55 0.25*2+0.2*1+0.1*9+0.3*8+0.15*7= 5.05
	Transition to Frozen	R-1 Independent Probe R-2 DataBase	9+6+9+5+5= 34 0+5+10+1+1= 17	0.25*9+0.2*6+0.1*9+0.3*5+0.15*5= 6.60 0.25*0+0.2*10+0.1*1+0.15*1= 2.45
	Below 32º F	S-1 Independent Probe S-2 DataBase S-3 Sampling and laboratory testing	9+6+9+5+5= 34 0+5+10+1+1=17 2+1+9+8+7= 27	0.25*9+0.2*6+0.1*9+0.3*5+0.15*5= 6.60 0.25*0+0.2*5+0.1*10+0.3*1+0.15*1= 2.45 0.25*2+0.2*1+0.1*9+0.3*8+0.15*7= 5.05

Table D-2. Testing and Calibration Matrix - Normalized Selection Factors

Sensor Parameter Direct Measurement	**Pavement Condition**	**Calibration Method**	**Time to Conduct Test Start/end**	**Annualized Cost of Equipment**	**Annualized Cost of Training**	**Absolute Accuracy**	**Precision (Resolution)**	**Comments**
Pavement Surface Temperature	Ambient pavement temp (dry) (below 50º F)	A-1 Hand held radiometer	Short (10)	Low (6)	Short (9)	Low (3)	Medium (4)	See notes at bottom of table
		A-2 Contact with Thermistor	Moderate (6)	Very Low (10)	Moderate (8)	High (10)	High (9)	See notes at bottom of table
		A-3. Database screening	NA (0)	Low (5)	Very Long (1)	Low (1)	Low (1)	See notes at bottom of table
	Ambient pavement temp (wet) (below 50º F)	B-1 Hand held radiometer	Short (10)	Low (6)	Short (9)	Low (3)	Medium (4)	See notes at bottom of table
		B-2. Water bath with Thermistor	Medium (4)	Very Low (9)	Moderate (8)	High (10)	High (9)	See notes at bottom of table
		B-3. Spray with Thermistor & paper towel	Medium (4)	Very Low (10)	Moderate (8)	High (10)	High (9)	See notes at bottom of table
		B-4. Database screening	N/A (0)	Low (5)	Very Long (1)	Low 91)	Low (1)	See notes at bottom of table
	Pavement temp. at 32º F	C-1 Ice bath with radiometer	Short (10)	Low (6)	Short (9)	Low (3)	Medium (4)	See notes at bottom of table
		C-2. Ice bath with Thermistor	Medium (4)	Very Low (9)	Moderate (8)	High (10)	High (9)	See notes at bottom of table
		C-3 Database screening	N/A (0)	Low (5)	Very Long (1)	Low (1)	Low (1)	See notes at bottom of table

	Pavement temp. below 32ºF forced	D-1 Dry ice with radiometer	Moderate (6)	Low (5)	Short (9)	Low (3)	Medium (4)	See notes at bottom of table
		D-2. Dry ice with Thermistor	Medium (3)	Very Low (9)	Moderate (8)	High (10)	High (10)	See notes at bottom of table
		D-3. Database Screening	N/A (0)	Low (5)	Very Long (1)	Low (1)	Low (1)	See notes at bottom of table
	Pavement temp. forced (wet condition w/ below 32ºF)	E-1 Salt brine bath with radiometer	Moderate (8)	Low (5)	Short (9)	Low (3)	Medium (6)	See notes at bottom of table
		E-2 Salt brine bath with thermistor	Moderate (6)	Very Low (9)	Moderate (8)	High (10)	High (10)	See notes at bottom of table
	Ambient Pavement temp below 32º	F-1 Hand held radiometer	Short (10)	Low (6)	Short (9)	Low (3)	Medium (4)	See notes at bottom of table
		F-2 Contact with Thermistor	Moderate (6)	Very Low (10)	Moderate (8)	High (10)	High (9)	See notes at bottom of table
		F-3. Database screening	N/A (0)	Low (5)	Very Long (1)	Low (1)	Low (1)	See notes at bottom of table
Pavement Condition	Dry Condition	G-1 Visual before, cleaning	Short (10)	Very Low (10)	Short (10)	High (10)	N/A (0)	See notes at bottom of table
		G-2. Visual, after cleaning	Short (10)	Very Low (10)	Short (10)	High (10)	N/A (0)	See notes at bottom of table
		G-3. Database screening	N/A (0)	Low (5)	Very Long (1)	Low (1)	N/A (0)	See notes at bottom of table

	Wet Condition	H-1 Visual - water	Short (10)	Very Low (10)	Short (10)	High (10)	N/A (0)	See notes at bottom of table
		H-2 Visual after cleaning	Short (10)	Very Low (10)	Short (10)	High (10)	N/A (0)	See notes at bottom of table
		H-3 Using a spray	Moderate (8)	Very Low (9)	Short (10)	High (9)	N/A (0)	See notes at bottom of table
		H-4 Ponding over sensor	Moderate (7)	Very Low (8)	Short (10)	High (8)	N/A (0)	See notes at bottom of table
	Freezing Condition	I-1 Visual – dry	Short (10)	Very Low (10)	Short (10)	High (10)	N/A (0)	See notes at bottom of table
		I-2 Visual after cleaning	Short (10)	Very Low (10)	Short (10)	High (10)	N/A (0)	See notes at bottom of table
		I-3 Using a spray	Moderate (6)	Very Low (9)	Short (9)	High (9)	N/A (0)	See notes at bottom of table
		I-4 Ponding over sensor	Medium (4)	Low (7)	Short (9)	High (9)	N/A (0)	See notes at bottom of table
		I-5 Database screening	N/A (0)	Low (5)	High (1)	Low (1)	N/A (0)	See notes at bottom of table
	Frost	J-1 Visual – Frost	Short (10)	Very Low (10)	Short (10)	High (10)	N/A (0)	See notes at bottom of table
		J-2 Database screening	N/A (0)	Low (5)	Very Long (1)	Low (1)	N/A (0)	See notes at bottom of table

Chemical concentration/ Freezing point	Salt brine (4,10,15, 20% & saturation concentrations)	K-1 Spraying solution K-2 Pouring solution	Medium (4) Medium (3)	Very Low (10) Very Low (10)	Moderate (8) Moderate (8)	Medium (6) Medium (4)	Medium (5) Medium (5)	See notes at bottom of table See notes at bottom of table
	Magnesium chloride (4,10,15, 20% & saturation concentrations)	L-1 Spraying solution L-2 Pouring solution	Medium (4) Medium (3)	Very Low (10) Very Low (10)	Moderate (8) Moderate (8)	Medium (6) Medium (4)	Medium (5) Medium (5)	See notes at bottom of table See notes at bottom of table
Surface State Ice Depth	No sensor identified	M-1 no method identified						
Subsurface Temperature	Above 32ºF	N-1 Independent probe N-2 Database N-3 Fixed Resistance	Long (1) N/A (0) Short (9)	High (1) Low (5) Short (10)	Short (9) High (1) Short (9)	Medium (5) Low (1) High (8)	Medium (5) Low (1) High (7)	See notes at bottom of table See notes at bottom of table See notes at bottom of table
	Transition to frozen	O-1 Independent probe O-2 Database O-3 Fixed Resistance	Long (1) N/A (0) Short (9)	High (1) Low (5) Short (10)	Short (9) High (1) Short (9)	Medium (5) Low (1) High (8)	Medium (5) Low (1) High (7)	See notes at bottom of table See notes at bottom of table See notes at bottom of table

	Below 32ºF	P-1 Independent probe P-2 Database P-3 Fixed Resistance	Long (1) N/A (0) Short (9)	High (1) Low (5) Medium (10)	Short (9) High (1) Short (9)	Medium (5) Low (1) High (8)	Medium (5) Low (1) High (7)	See notes at bottom of table See notes at bottom of table See notes at bottom of table
Subsurface Moisture	Above 32ºF	Q-1 Independent probe Q-2 Database Q-3 Sampling and laboratory testing	Short (9) N/A (0) Long (2)	Low (6) Low (5) High (1)	Short (9) High (1) Short (9)	Medium (5) Low (1) High (8)	Medium (5) Low (1) High (7)	See notes at bottom of table See notes at bottom of table See notes at bottom of table
	Freeze/ thaw transition	R-1 Independent probe R-1 Database	Short (9) N/A (0)	Low (6) Low (5)	Short (9) High (10)	Medium (5) Low (1)	Medium (5) Low(1)	See notes at bottom of table See notes at bottom of table
	Below 32	S-1 Independent probe S-2 Database S-3 Sampling and laboratory testing	Short (9) N/A (0) Long (2)	Low (6) Low (5) High (1)	Short (9) High (10) Short (9)	Medium (5) Low (1) High (8)	Medium (5) Low (1) High (7)	See notes at bottom of table See notes at bottom of table See notes at bottom of table

Notes for testing procedures:

A. Ambient pavement temperature (Dry condition) (Below 50º F)

- Recommend sensor be tested at night so that solar radiation is not a factor.
- If night time testing is not possible, the sensor must be shaded from solar radiation for a period of 30 minutes before taking readings. Use beadboard not in contact with the surface. *Note: An umbrella may be substituted for beadboard.*
- Sensor surface should be dry and the ambient temperature of the pavement must be below 50º F.

A-1 Hand held Radiometer:

- Confirm that the emissivity is set correctly on the device and that the device is calibrated.
- Point the instrument at the sensor surface.
- Depress the trigger and record the temperature reading on the LCD screen.
- Record the temperature reading on the LCD screen.
- Take at least 3 or 5 readings on the sensor surface and record the readings. More readings may have to be taken until stability of the pavement temperature is observed.
- Obtain and record output readings from the sensor.

A-2 Contact with Thermistor:

- Attach the thermistor to the top of the pavement with approved thermally conductive paste material.
- Cover the both the thermistor and the sensor to block the effects of the environment. Use beadboard not in contact with the surface.
- Take and record at least 3 or 5 readings from both the thermistor and the sensor. More readings may have to be taken until stability of the pavement temperature is observed from the thermistor.

A-3 Database screening:

- Range Checks
  Sensors have a range of readings that are considered normal. Thus, it is possible to identify as defective, those sensors whose data values consistently fall outside the normal range or have a predefined temperature values.
- Neighborhood Associations
  Comparison of RWIS pavement sensor data with sensor data generated at other RWIS stations in the immediate vicinity.
- Seasonal Associations
  An analysis of historical data for a given period of time may reveal a range of sensor readings that would appear to be normal for a particular season period.
- Temporal Analysis
  Similar to seasonal analysis except the window of readings is limited to hours rather than days.

B. Ambient pavement temperature (Wet condition) (Below 50º F)

- Recommend sensor be tested at night so that solar radiation is not a factor.
- If nighttime testing is not possible, the sensor should be shaded from solar radiation for a period of 30 minutes before taking readings.
- Sensor surface should be wet. Spray the surface of the sensor with tap water. Check the water film thickness by sucking the water into filter paper and measuring the increase in weight per surface area. Recommended thickness is 0.5 mm.
- The ambient temperature of the pavement must be below 50º F.

B-1 Hand held radiometer:

- Confirm that the emissivity is set correctly on the device and that the device is calibrated.
- Point the instrument at the sensor surface.
- Depress the trigger and record the temperature reading on the LCD screen.
- Record the temperature reading on the LCD screen.
- Take 3 or 5 readings on the sensor surface and record the readings.

- Obtain and record output readings from the sensor.

B-2 Water bath with Thermistor:

- Create a watertight form on top of the pavement surface surrounding the pavement sensor.
- Fill the area inside the form, on top of the pavement section with tap water to create a bath.
- Submerge the thermistor in the water bath. Wait 10 minutes or more for the temperature readings from sensor and thermistor are stabilized.
- Take and record 3 or 5 temperature readings from the pavement sensor and the thermistor.

B-3 Spray sensor and use a Thermistor with paper towel:

- Attach the thermistor to the top of the pavement sensor with approved sealant material.
- Spray the top of the sensor with tap water. Check and record the thickness of the water film thickness.
- Cover the both the thermistor and the sensor to block the effects of the environment.
- Take and record 3 or 5 readings from both the thermistor and the sensor. More readings may have to be taken until stability of the pavement temperature is observed from the thermistor.

B-4 Database screening

See A-3

C. Pavement temperature (Wet condition) (at 32º F)

- Create the required condition by using an ice/water bath.
- Create a watertight form on top of the pavement surface surrounding the pavement sensor.
- Fill the area inside the form, on top of the pavement section, with ice and tap water to create a bath.

C-1 Ice bath with hand held radiometer:

- Wait 10 minutes or more for the pavement sensor to stabilize.
- Confirm that the emissivity is set correctly on the device and that the device is calibrated.
- Point the instrument at the ice/water bath surface.
- Depress the trigger and record the temperature reading on the LCD screen.
- Record the temperature reading on the LCD screen.
- Take 3 or 5 readings on the ice/water bath surface and record the readings.
- Obtain and record output readings from the sensor.

C-2 Ice bath with thermistor:

- Submerge the thermistor in the ice bath.
- Wait 10 minutes or more for the sensor and thermistor to stabilize.
- Take and record 3 or 5 temperature readings from the pavement sensor and the thermistor.

C-3 Database screening:

See A-3

D. Pavement temperature (Dry condition) (Forced below 32º F)

Create the condition by applying dry ice to the surface of the pavement sensor.

D-1 Dry ice with hand held radiometer:

- Cool the surface with dry ice.
- Confirm that the emissivity is set correctly on the device and that the device is calibrated.
- Point the instrument at the sensor surface.
- Depress the trigger and record the temperature reading on the LCD screen.
- Take 3 or 5 readings on the sensor surface and record the readings.
- Obtain and record output readings from the sensor.

D-2 Dry ice with thermistor:

- Attach the thermistor to the top of the pavement sensor with approved thermally conductive paste material.
- Cool the surface with dry ice.
- Cover the both the thermistor and the sensor with bead board that is not in contact with the surface to reduce heating.
- Verify pavement temperature is below 32º F.
- Take and record 3 or 5 readings from both the thermistor and the sensor.

D-3 Database Screening:

See A-3

E. Pavement temperature (Wet condition) (Forced below 32º F)

Create the condition by using salt brine and ice bath.

E-1 Salt brine and ice bath with hand held radiometer:

- Create a watertight form on top of the pavement surface surrounding the pavement sensor.
- Fill the area inside the form, on top of the pavement section, with a saturated solution of salt brine and ice to create a brine bath.
- Wait 10 minutes or more for the pavement sensor to stabilize.
- Confirm that the emissivity is set correctly on the device and that the device is calibrated.
- Point the instrument at the surface of the brine bath.
- Depress the trigger and record the temperature reading on the LCD screen.
- Record the temperature reading on the LCD screen.
- Take 3 or 5 readings on the brine bath surface and record the readings.
- Obtain and record output readings from the sensor.

E-2 Salt brine and ice bath with thermistor:

- Create a watertight form on top of the pavement surface surrounding the pavement sensor.
- Fill the area inside the form, on top of the pavement section, with a saturated solution of salt brine and ice to create a brine bath.
- Submerge the thermistor in the brine bath.
- Wait 10 minutes or more for both the pavement sensor and thermistor to stabilize.
- Take and record 3 or 5 temperature readings from the pavement sensor and the thermistor.

E-3 Database screening:

See A-3

F. Ambient pavement temperature (Existing conditions) (Existing below 32º F)

- Utilize existing conditions when the pavement temperature is reporting to be below 32º F.

F-1 Hand held radiometer:

- Confirm that the emissivity is set correctly on the device and that the device is calibrated.
- Point the instrument at the sensor surface.
- Depress the trigger and record the temperature reading on the LCD screen.
- Record the temperature reading on the LCD screen.
- Take at least 3 or 5 readings on the sensor surface and record the readings. More readings may have to be taken until stability of the pavement temperature is observed.
- Obtain and record output readings from the sensor.

F-2 Contact with thermistor:

- Attach the thermistor to the top of the pavement sensor with approved thermally conductive paste material.
- Cover the both the thermistor and the sensor with bead board that is not in contact with the surface to block the effects of the environment.
- Take and record at least 3 or 5 readings from both the thermistor and the sensor. More readings may have to be taken until stability of the pavement temperature is observed.

F-3 Database screening:

See A-3

Pavement Condition

G. Dry Condition

G-1 Visual before cleaning:

- Observe the condition of the top of the pavement surface
- Record the manual observation and the read out from the pavement sensor

G-2 Visual after cleaning:

- Clean the top of the pins on the sensor with a brass brush and dry the surface with dry cloth.
- Observe the condition of the top of the pavement surface
- Record the manual observation and the read out from the pavement sensor

G-3 Database screening:

- Range Checks

Sensors have a range of readings that are considered normal. Thus, it is possible to identify as defective, those sensors whose data values consistently fall outside the normal range or have a predefined temperature values.

- Neighborhood Associations
  Comparison of RWIS pavement sensor data with sensor data generated at other RWIS stations in the immediate vicinity.
- Seasonal Associations
  An analysis of historical data for a given period of time may reveal a range of sensor readings that would appear to be normal for a particular season period.
- Temporal Analysis
  Similar to seasonal analysis except the window of readings is limited to hours rather than days.

H. Wet Conditions

H-1 Visual:

- Wet the surface of the sensor with tap water.
- Observe the condition of the top of the pavement surface
- Record the observation and the read out from the pavement sensor

H-2 Visual after cleaning:

- Clean the top of the pins on the sensor with a brass brush.
- Wet the surface of the sensor with tap water.
- Observe the condition of the top of the pavement surface
- Record the observation and the read out from the pavement sensor

H-3 Spray the sensor with visual observation: (try to develop a water film thickness of 0.5 mm.)

- Spay the top of the sensor with tap water
- Observe the condition of the top of the pavement surface
- Check the water film thickness by sucking the water into filter paper and measuring the increase in weight per surface area. Record the thickness of the water film.
- Record the observation, water film thickness, and the read out from the pavement sensor

H-4 Ponding water over sensor

- Create a watertight form on top of the pavement surface,
- Fill the area inside the form, on top of the pavement section, with tap water.
- Record the observation and the read out from the pavement sensor

I. Freezing Conditions

- Observations can be conducted only when the pavement temperature is below 32º F.

I-1 Visual when pavement is dry

- Observe the condition of the top of the pavement surface
- Record the observation and the read out from the pavement sensor

I-2 Visual after cleaning of pins while pavement is dry

- Clean the top of the pins on the sensor with a brass brush.
- Observe the condition of the top of the pavement surface
- Record the observation and the read out from the pavement sensor

I-3 Visual after using a spray:

- Clean the top of the pins on the sensor with a brass brush.
- Spay the top of the sensor with tap water.
- Wait for the water to freeze to ice.
- Observe the condition of the top of the pavement surface.
- Record the observation and the read out from the pavement sensor

I-4 Visual after ponding over sensor:

- Create a watertight form on top of the pavement surface surrounding the pavement sensor.
- Fill the area inside the form, on top of the pavement section, with tap water.
- Wait for the water to freeze to ice.
- Record the observation and the read out from the pavement sensor.

J. Frost

- Frost condition cannot be created in the field. It can only be observed.

J-1 Visual:

- When the RWIS site is reporting frost condition, human observation is required.
- Record the observation and the read out from the pavement sensor.

J-2 Database screening:

See G-3

Chemical concentration/Freezing point

In order to conduct these observations, the pavement temperature will need to be at least 3º C colder than the freezing point of the solution.

K. Salt brine (4%, 10%, 15%, and saturation concentrations)

The solutions will be prepared in accordance with the guidelines contained in Publication No. FHWA-RD-95-202, "Manual of Practice for an Effective Anti-icing Program: A Guide for Highway Winter Maintenance Personnel", Appendix A. Selected chemicals and Their Properties.

K-1 Spraying solution

- Clean the tops of the pins and surface of the sensor with distilled water.
- Spray enough known salt brine solution on top of the sensor to approximate 0.5 mm of film thickness.
- Check the water film thickness by sucking the water into filter paper and measuring the increase in weight per surface area. Record the thickness of the water film.
- Wait **?** minutes for the sensor to process the data.
- Record the valves from the output of the pavement sensor and theoretical freezing point of the applied salt brine.

K-2 Ponding solutions

- Clean the tops of the pins and surface of the sensor with distilled water.
- Create a watertight form on top of the pavement surface surrounding the pavement sensor.
- Flood the area on top of the pavement section and inside the form with known salt brine to a thickness of approximately 4 mm.
- Wait **X** minutes for the sensor to process the data.Record the valves from the output of the pavement sensor and theoretical freezing point of the applied salt brine.

L. Magnesium chloride brine (4%, 10%, 15%, and saturation concentrations)

The solutions will be prepared in accordance with the guidelines contained in Publication No. FHWA-RD-95-202, "Manual of Practice for an Effective Anti-icing Program: A Guide for Highway Winter Maintenance Personnel", Appendix A. Selected chemicals and Their Properties.

L-1 Spraying solution

- Clean the tops of the pins and surface of the sensor with distilled water.
- Spray enough known magnesium chloride brine solution on top of the sensor to approximate 0.5 mm of film thickness.
- Wait **X** minutes for the sensor to process the data.
- Record the valves from the output of the pavement sensor and theoretical freezing point of the applied magnesium chloride brine.

L-2 Ponding solutions

- Clean the tops of the pins and surface of the sensor with distilled water.
- Create a watertight form on top of the pavement surface surrounding the pavement sensor.
- Fill the area inside the form, on top of the pavement section, with know magnesium chloride brine.
- Wait **?** minutes for the sensor to process the data.
- Record the valves from the output of the pavement sensor and theoretical freezing point of the applied magnesium chloride brine.

Sub-surface Temperature

These temperature sensors are either located 18 inches below the top of the pavement surface or 3 to 4 cm below the surface.

N. Above 32º F

N-1 Independent probe:

- Install an independent probe by drilling a hole in the roadbed outside of the roadway surface.
- Install a thermistor in the drilled hole at the same elevation as the subject sensor. If the subject sensor has a number of elements that measures temperature at various elevations, it will be necessary to place referenced thermistors at those elevations.
- Backfill the drilled hole with the bore cuttings.
- Wait for two hours for the thermistor to stabilize with surrounding material and the roadbed.
- Observe and record the readings from the independent probe and sub-surface temperature sensor.

N-2 Database screening:

- Range Checks
  Sensors have a range of readings that are considered normal. Thus, it is possible to identify as defective, those sensors whose data values consistently fall outside the normal range or have a predefined temperature values.
- Neighborhood Associations
  Comparison of RWIS sub-surface sensor data with sensor data generated at other RWIS stations in the immediate vicinity.
- Seasonal Associations
- An analysis of historical data for a given period of time may reveal a range of sensor readings that would appear to be normal for a particular season period.
- . Temporal Analysis
- Similar to seasonal analysis except the window of readings is limited to hours rather than days.

N-3 Fixed resistance:

- Conduct a resistance reading on the sensor.
- Using resistance charts for the sensor, compare the temperature value with the output of the sensor.

O. Transition to Frozen

O-1 Independent probe:

- Install an independent probe by drilling a hole in the roadbed outside of the roadway surface.
- Install a thermistor in the drilled hole at the same elevation as the subject sensor. If the subject sensor has a number of elements that measures temperature at various elevations, it will be necessary to place referenced thermistors at those elevations.
- Backfill the drilled hole with the bore cuttings.
- Wait for two hours for the thermistor to stabilize with surrounding material and the roadbed.
- Observe and record the readings from the independent probe and sub-surface temperature sensor.

O-2 Database screening:

See N-2

O-3 Fixed Resistance:

- Conduct a resistance reading on the sensor.
- Using resistance charts for the sensor, compare the temperature value with the output of the sensor.

P. Below 32º F

P-1 Independent probe

- Install an independent probe by drilling a hole in the roadbed outside of the roadway surface.
- Install a thermistor in the drilled hole at the same elevation as the subject sensor. If the subject sensor has a number of elements that measures temperature at various elevations, it will be necessary to place referenced thermistors at those elevations.
- Backfill the drilled hole with the bore cuttings.
- Wait for two hours for the thermistor to stabilize with surrounding material and the roadbed.
- Observe and record the readings from the independent probe and sub-surface temperature sensor.

P-2 Database screening

See N-2

P-3 Fixed Resistance:

- Conduct a resistance reading on the sensor.
- Using resistance charts for the sensor, compare the temperature value with the output of the sensor.

Sub-surface Moisture

- Sensor use to measure moisture content of the subgrade material.

Q. Above 32º F

Q-1 Independent probe

- Install an independent probe by drilling a hole in the roadbed outside of the roadway surface.
- Install a similar moisture probe that has been calibrated in the drilled hole at the same elevations as the subject sensor. If the subject sensor has a number of elements that measures moisture at various elevations, it will be necessary to place referenced sensor at those elevations.
- Backfill the drilled hole with the bore cuttings.
- Wait for 24 hours for the probe to stabilized with surrounding material and the roadbed.
- Observe and record the readings from the independent probe and sub-surface moisture sensor.

Q-2 Database screening

- Range Checks

  Sensors have a range of readings that are considered normal. Thus, it is possible to identify as defective, those sensors whose data values consistently fall outside the normal range or have a predefined temperature values.
- Neighborhood Associations

  Comparison of RWIS sub-surface sensor data with sensor data generated at other RWIS stations in the immediate vicinity.
- Seasonal Associations

  An analysis of historical data for a given period of time may reveal a range of sensor readings that would appear to be normal for a particular season period.
- Temporal Analysis

  Similar to seasonal analysis except the window of readings is limited to hours rather than days.

Q-3 Sampling and Laboratory Testing:

- Conduct an auger boring in the roadbed material
- Collect soil moisture samples at the same elevation as the subject sub-surface moisture sensor.
- Observe and record the moisture content readings from the sub-surface moisture sensor.
- Conduct laboratory analyses to determine the moisture content and record the values.

R. Freeze/thaw transition

R-1 Independent probe:

See Q-1

R-2 Database Screening:

See Q-2

S. Below 32º F

S-1 Independent Probe:

See Q-1

S-2 Database Screening:

See Q-2

S-3 Sampling and Laboratory Testing:

See Q-3

Normalized Selection Factors

Table D-3. Pavement Surface Temperature

Time to Test Start/End (Weighting Factor 25 %)

Ranges used in Survey	Terminology used in Table E-2	Point Range
Less than 1 hour	Short	9 to 10
1 to 2 hours	Moderate	5 to 8
2 to 3 hours	Medium	3 to 4
3 to 4 hours	Long	1 to 2

Annualized Cost of Equipment (Weighting Factor 20 %)

Ranges	Terminology used in Table E-2	Point Range
Less than $99	Very Low	9 to 10
$100 to $299	Low	5 to 8
$300 to $499	Moderate	3 to 4
More than $500	High	1 to 2

Annualized Cost of Training (Weighting Factor 10 %)

Ranges used in Survey	Terminology used in Table E-2	Point Range
Less than ½ day	Short	9 to 10
½ to 1 day	Moderate	5 to 8
1 to 2 days	Long	3 to 4
More than 2 days	Very Long	1 to 2

Absolute Accuracy (Weighting Factor 30 %)

Range	Terminology used in Table E-2	Points Range
1 to 5 º F	Low	1 to 3
0.5 to 0.9 º F	Medium	4 to6
0.05 to 0.5 º F	High	7 to 10

Precision (Resolution) (Weighting Factor 15 %)

Range	Terminology used in Table E-2	Points Range
5º F	Low	1 to 3
1º F	Medium	4 to 6
0.1º F	High	7 to 10

Table D-4. Pavement Condition

Time to Test Start/End (Weighting Factor 25 %)

Ranges used in Survey	Terminology used in Table E-2	Point Range
Less than 1 hour	Short	9 to 10
1 to 2 hours	Moderate	5 to 8
2 to 3 hours	Medium	3 to 4
3 to 4 hours	Long	1 to 2

Annualized Cost of Equipment (Weighting Factor 20 %)

Ranges	Terminology used in Table E-2	Point Range
Less than $99	Very Low	9 to 10
$100 to $299	Low	5 to 8
$300 to $499	Moderate	3 to 4
More than $500	High	1 to 2

Annualized Cost of Training (Weighting Factor 10 %)

Ranges used in Survey	Terminology used in Table E-2	Point Range
Less than ½ day	Short	9 to 10
½ to 1 day	Moderate	5 to 8
1 to 2 days	Long	3 to 4
More than 2 days	Very Long	1 to 2

Absolute Accuracy (Weighting Factor 30 %)

Range	Terminology used in Table E-2	Point Range
Able to Determine	High	8 to 10
Not able to Determine	Low	1

Precision (Resolution) (Weighting Factor 15 %)

Range	Terminology used in Table E-2	Point Range
N/A		

Table D-5. Chemical Concentration/Freezing Point

Time to Test Start/End (Weighting Factor 25 %)

Ranges used in Survey	Terminology used in Table E-2	Point Range
Less than 1 hour	Short	9 to 10
1 to 2 hours	Moderate	5 to 8
2 to 3 hours	Medium	3 to 4
3 to 4 hours	Long	1 to 2

Annualized Cost of Equipment (Weighting Factor 20 %)

Ranges	Terminology used in Table E-2	Point Range
Less than $99	Very Low	9 to 10
$100 to $299	Low	5 to 8
$300 to $499	Moderate	3 to 4
More than $500	High	1 to 2

Annualized Cost of Training (Weighting Factor 10 %)

Ranges used in Survey	Terminology used in Table E-2	Point Range
Less than ½ day	Short	9 to 10
½ to 1 day	Moderate	5 to 8
1 to 2 days	Long	3 to 4
More than 2 days	Very Long	1 to 2

Absolute Accuracy (Weighting Factor 10 %)

Range	Terminology used in Table E-2	Point Range
5 to 10º F	Low	1 to 3
1 to 4.9 º F	Medium	4 to6
0.1 to 0.9 º F	High	7 to 10

Precision (Resolution) (Weighting Factor 15 %)

Range	Terminology used in Table E-2	Point Range
5º F	Low	1 to 3
1º F	Medium	4 to 6
0.1º F	High	7 to 10

Table D-6. Sub-surface Temperature

Time to Test Start/End (Weighting Factor 25 %)

Ranges used in Survey	Terminology used in Table E-2	Point Range
Less than 1 hour	Short	9 to 10
1 to 2 hours	Moderate	5 to 8
2 to 3 hours	Medium	3 to 4
3 to 4 hours	Long	1 to 2

Annualized Cost of Equipment (Weighting Factor 20 %)

Ranges	Terminology used in Table E-2	Point Range
Less than $99	Very Low	9 to 10
$100 to $299	Low	5 to 8
$300 to $499	Moderate	3 to 4
More than $500	High	1 to 2

Annualized Cost of Training (Weighting Factor 10 %)

Ranges used in Survey	Terminology used in Table E-2	Point Range
Less than ½ day	Short	9 to 10
½ to 1 day	Moderate	5 to 8
1 to 2 days	Long	3 to 4
More than 2 days	Very Long	1 to 2

Absolute Accuracy (Weighting Factor 30 %)

Range	Terminology used in Table E-2	Point Range
1 to 5 º F	Low	1 to 3
0.5 to 0.9 º F	Medium	4 to6
0.05 to 0.5 º F	High	7 to 10

Precision (Resolution) (Weighting Factor 15 %)

Range	Terminology used in Table E-2	Point Range
5º F	Low	1 to 3
1º F	Medium	4 to 6
0.1º F	High	7 to 10

Table D-7. Sub-Surface Moisture

Time to Test Start/End (Weighting Factor 25 %)

Range	Terminology used in Table E-2	Point Range
Less than 1 hour	Short	9 to 10
1 to 2 hours	Moderate	5 to 8
2 to 3 hours	Medium	3 to 4
3 to 4 hours	Long	1 to 2

Annualized Cost of Equipment (Weighting Factor 20 %)

Range	Terminology used in Table E-2	Point Range
Less than $99	Very Low	9 to 10
$100 to $299	Low	5 to 8
$300 to $499	Moderate	3 to 4
More than $500	High	1 to 2

Annualized Cost of Training (Weighting Factor 10 %)

Range	Terminology used in Table E-2	Point Range
Less than ½ day	Short	9 to 10
½ to 1 day	Moderate	5 to 8
1 to 2 days	Long	3 to 4
More than 2 days	Very Long	1 to 2

Absolute Accuracy (Weighting Factor 30 %)

Range	Terminology used in Table E-2	Points Range
5 to 20 %	Low	1 to 3
1 to 4.9 %	Medium	4 to6
0.1 to 0.9 %	High	7 to 10

Precision (Resolution) (Weighting Factor 15 %)

Range	Terminology used in Table E-2	Points Range
5 %	Low	1 to 3
1 %	Medium	4 to 6
0.1 %	High	7 to 10

APPENDIX E
QUALITY CONTROL - MADIS APPROACH

The following sections detail the quality control procedures developed for the National Weather Service's Meteorological Assimilation Data Ingest System. The information in this section relates to automated quality control, subjective interpretation and QC data structures.

Automated Quality Control

These checks are run with an algorithm on collected data. They have three levels which comprise four categories. Level 1 QC checks are considered the least sophisticated and level 3 are the most sophisticated checks. Table F-2 lists the surface variables that are quality controlled and the checks that are used [1]. However, it should be noted that while the QC checks discussed here are generally applied to the form of the variable stored in the database, the QC results will also be applied to any forms of the variable that are requested by the user and are derived from the primary variable. For example, specific humidity will get the QC results from the checks applied to dew point temperature.

The level 1 validity checks restrict each observation to falling within a TSP-specified set of tolerance limits, while the level 2 temporal consistency checks restrict the temporal rate of change of each observation to a set of TSP-specified tolerance limits. In both cases, observations not falling within the limits are flagged as failing the respective QC check. The following tables Table F-3 and F-4 list the tolerance limits:

Table E-1. Level 1 Validity Checks

Dewpoint temperature	-90 to 90 F
Relative humidity	0 to 100%
Altimeter	568 to 1100mb
Pressure change	0 to 30.5mb
Sea level pressure	846 to 1100mb
Station pressure	568 to 1100mb
Air temperature	-60 to 130 F
Wind Direction	0 to 360deg
Wind Speed	0 to 250kts
Visibility	0 to 100 miles
Accumulated precip to *h	0 to 44in

Table E-2. Level 2 Temporal Consistency Checks

Dewpoint temperature	35 F/hour
Sea level pressure	15 mb/hour
Air temperature	35 F/hour
Wind speed	20 kts/hour

The level 2 internal consistency checks enforce reasonable, meteorological relationships among observations measured at a single station. For example, a dew point temperature observation must not exceed the temperature observation made at the same station. If it does, both the dew point and temperature observation are flagged as failing their internal consistency checks. Pressure internal consistency checks include a comparison of pressure change observations at each station with the difference of the current station pressure and the station pressure three hours earlier. It also includes a comparison of the reported sea-level pressure with a sea-level pressure estimated from the station pressure and the 12-hour mean surface temperature. In the former check, if the reported three hour pressure change observation does not match the calculated observation, then only the reported observation is flagged as bad. In the latter check, however, if the reported sea-level pressure does not match the calculated observation, then both the sea-level and station pressure observation are flagged as failing. Table F-5 lists the Internal Consistency Checks for surface observations.

The level 2 internal consistency checks enforce reasonable, meteorological relationships among observations measured at a single station. For example, a dew point temperature observation must not exceed the temperature observation made at the same station. If it does, both the dew point and temperature observation are flagged as failing their internal consistency checks. Pressure internal consistency checks include a comparison of pressure change observations at each station with the difference of the current station pressure and the station pressure three hours earlier. It also includes a comparison of the reported sea-level pressure with a sea-level pressure estimated from the station pressure and the 12-hour mean surface temperature. In the former check, if the reported three hour pressure change observation does not match the calculated observation, then only the reported observation is flagged as bad. In the latter check, however, if the reported sea-level pressure does not match the calculated observation, then both the sea-level and station pressure observation are flagged as failing. Table F-5 lists the Internal Consistency Checks for surface observations.

The level 3 spatial consistency (or "buddy") check is performed using an Optimal Interpolation (OI) technique developed by Belousov et al. [2]. At each observation location, the difference between the measured value and the value analyzed by OI is computed. If the magnitude of the difference is small, the observation agrees with its neighbors and is considered correct. If, however, the difference is large, either the observation being checked or one of the observations used in the analysis is bad. To determine which is the case, a reanalysis of the observation location is performed by eliminating one neighboring observation at a time. If successively eliminating each neighbor does not produce an analysis that agrees with the target observation (the observation being checked), the observation is flagged as bad. If eliminating one of the neighboring observations produces an analysis that agrees with the target observation, then the target observation is flagged as "good" and the neighbor is flagged as "suspect." Suspect observations are not used in subsequent OI analyses. Figure E-1 illustrates the reanalysis procedure.

Table E-3, MADIS Surface Variables with QC [3]

			Level 1:	Level 2:		Level 3:
Code	Name	Maximum Possible QC Level	Validity	Internal Consistency	Temporal Consistency	Spatial Consistency
TD	dewpoint temperature	3	X	3	X	X
RH	relative humidity	3	X	3	X	X
Q	specific humidity	3	X	3	X	X
DPD	dewpoint depression	3	X	3	X	X
AH	absolute humidity	3	X	3	X	X
ALTSE	altimeter	3	X		X	X
PT3	3 hour pressure change	2	X	2		
SLP	sea level pressure	3	X	1	X	X
P	station pressure	3	X	1	X	X
T	air temperature	3	X	3	X	X
TV	virtual temperature	3	X	3	X	X
DD	wind direction	3	X		X	X
FF	wind speed	3	X		X	X
U	u wind component	3	X		X	X
V	v wind component	3	X		X	X
VIS	visibility	1	X			
PCP1H	accumulated precip - 1h	1	X			
PCP3H	accumulated precip - 3h	1	X			
PCP6H	accumulated precip - 6h	1	X			
PCP12H	accumulated precip - 12h	1	X			
PCP18H	accumulated precip - 18h	1	X			
PCP24H	accumulated precip - 24h	1	X			
PCPLM	accum. precip - since local midnight	1				
PCPUTCM	accum. precip - since UTC midnight	1	X			
PCPRATE	precipitation rate	1	X			

Table E-4. Level 2 Internal Consistency Checks

1	Sea level pressure vs. station pressure
2	3h pressure change vs. station pressure
3	Air temperature vs. dewpoint temperature

To improve the performance of the OI, RSAS analysis fields from the previous hour are used as background grids. The analyses provide an accurate 1 hour persistence forecast and allow the incorporation of previous surface observations, thus improving temporal continuity near stations that report less frequently than hourly. The differences between the observations and the background are calculated and then interpolated to each observation point before the OI analysis is performed. In addition, uniform distribution of the neighboring observations used in the spatial consistency check is guaranteed when possible by a search algorithm which locates the nearest observation in each of eight directional sectors distributed around the target observation.

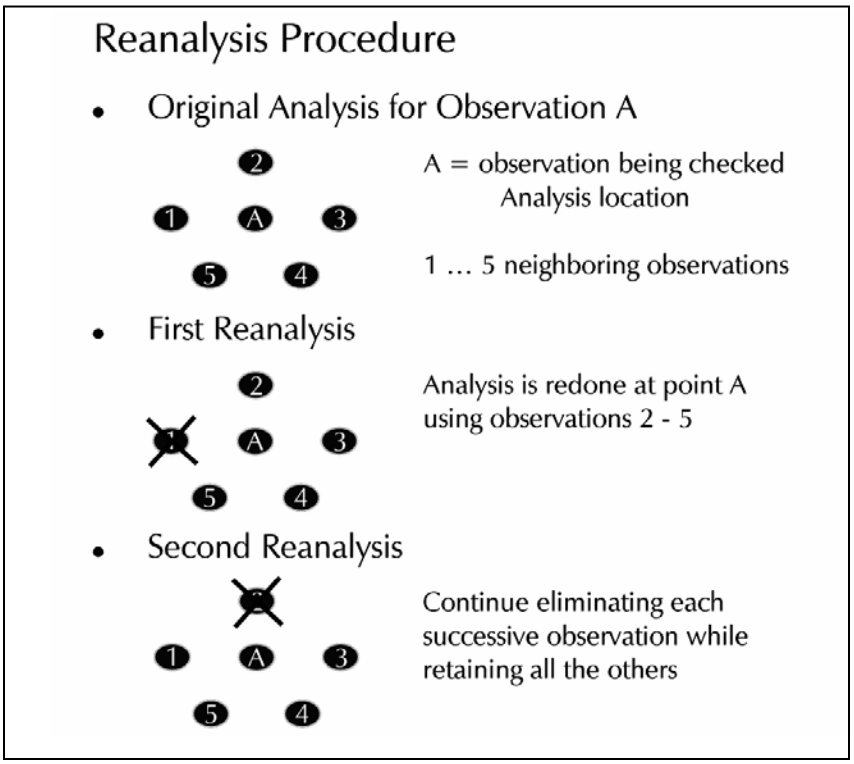

Figure E-1 Reanalysis Procedure

Temperature observations are converted to potential temperature before application of the spatial consistency check. Potential temperature varies more smoothly over mountainous terrain when the boundary layer is relatively deep and well mixed, a marked advantage during daytime hours. For example, potential temperature gradients associated with fronts tend to be well defined during the day even in mountainous terrain [4]. Unfortunately, this advantage often disappears at night when cool air pools in valleys. To improve the effectiveness of the spatial consistency check in these circumstances, elevation differences are incorporated to help model the horizontal correlation between mountain stations. [5]. The error threshold (to which the absolute value of the difference between analyzed and observed values is compared) is a function of the forecast error, the observational measurement error and the expected analysis error [1].

The MADIS processing at FSL also keeps surface data statistics on the frequency and magnitude of the observational errors encountered for NWS sea-level pressure, potential temperature, dew point and surface wind. At the completion of each hourly analysis, the system provides the total number of observations for each variable, the number of observations that failed the QC check, the station names for the failed observations and the error and threshold values for each of the failed observations. The error is defined as the difference between the QC analysis value and the observed value, as computed in the spatial consistency check.

Statistics are calculated for all stations. Stations from different networks are kept statistically separate. Specifically, the following stratifications are currently maintained: "ASOS," "SAO" (METAR manual), "AUTO" (METAR automated, but not ASOS), "BUOY," and "NPN" (NOAA Profiler Network). Local mesonets are stratified by provider. For example, "CDOT," for the Colorado Department of Transportation.

Current hourly, daily, weekly and monthly QC messages generated at FSL are available for the various surface-observing networks.

Subjective Intervention

Two text files, a "reject" and an "accept" list provide the capability to subjectively override the results of the automated QC checks. The reject list is a list of stations and associated input observations that will be labeled as bad, regardless of the outcome of the QC checks; the accept list is the corresponding list of stations that will be labeled as good, regardless of the outcome of the QC checks. In both cases, observations associated with the stations in the lists can be individually flagged. For example, wind observations at a particular station may be added to the reject list, but not the temperature observations.

Subjective intervention lists, with the sole exception that observations on the reject list will be labeled as “suspect” and not used to check the spatial consistency of neighboring observations, do not affect QC and station monitoring procedures. This will allow FSL personnel to continue to monitor the performance of the stations contained in the lists. For example, a station with wind observations that fail the QC checks a large percentage of the time may be added to the reject list. However, once the observation failure rate at the station falls back to near zero (possibly due to an anemometer that has been repaired), the station will likely be deleted from the list.

QC Data Structures

The MADIS QC information available for each variable includes the following QC structures:

- A single-character "data descriptor", intended to define an overall opinion of the quality of each observation by combining the information from the various QC checks, and for users desiring detailed information. (Table F-6)
- A "QC applied" bitmap indicating which QC checks were applied to each observation (Table F-7)
- A "QC results" bitmap indicating the results of the various QC checks.

Table E-6 provides a complete list of the data descriptors.

Table E-5, Data Descriptor Definitions [6]

Type of Check	Data Descriptor Character	Data Descriptor
Preliminary	(Z)	No QC Applied
Coarse Pass	(C)	Passed Level 1
Screened	(S)	Passed Levels 1 & 2
Verified	(V)	Passed Levels 1, 2, & 3
Erroneous	(X)	Failed Level 1
Questionable	(Q)	Passed Level 1, but failed Levels 2 or 3
Subjective Good	(G)	Included in accept list
Subjective Bad	(B)	Included in reject list

Two components of the QC metadata are whether the check was applied and the outcome of the check. Table F-7 provides the bitmask for each type of QC check. By examining the “applied” bits, the user can determine which checks were actually applied and by using the “results” bits, the user can determine the pass/fail status of each check. For example, a binary bit value of 1 for the applied check means the corresponding check was applied. A bit value of 0 indicates that the check was not applied. In the QC results, a bit value of 1 means the corresponding check was applied and failed, a bit value of 0 indicates the check passed.

The "Master Check" is used to summarize all of the checks in a single bit. If any check at all was applied, this bit will be set in the QC “applied” data. If the observation failed any QC check, it will be set in the QC “results” data.

When read as decimal numbers, the different bits that are set in the bitmask are summed together. For example, a QC applied value of 67 should be interpreted as 1 + 2 + 64, meaning the validity and spatial consistency checks were applied.

Table E-6, Bitmask for QC Applied and QC Results

Bit	QC Check	Decimal Value
1	Master Check	1
2	Validity Check	2
3	Reserved	4
4	Internal Consistency Check	8
5	Temporal Consistency Check	16
6	Reserved	32
7	Spatial Consistency Check	64
8	Reserved	128
9	Reserved	256
10	Reserved	512

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APPENDIX F
LABORATORY VALIDATION TEST PLAN

NOTE: This Validation Test Plan has been modified to reflect the updated methodology found during initial validation testing. The portion of this Validation Test Plan pertaining to field testing has been revised and updated and is presented in Appendix J. For more information refer to the *Draft Field Test Plan*, or to Appendix J – Field Test Plan.

This appendix contains a listing of equipment and supplies along with the step-by-step procedures required to conduct validation-testing of the pavement sensor test methods. Three different parameters will be tested: pavement temperature, pavement surface moisture conditions, and freezing point for varying concentrations of chemical de-icing solutions. These test plans are detailed in test plans 1, 2 and 3 respectively.

VALIDATION TEST PLAN 1: DETERMINATION OF PAVEMENT SURFACE TEMPERATURE

The goal of Validation Test Plan 1 is to validate the field test procedures for determining whether the pavement sensor is accurately monitoring pavement temperature.

For each test, the following equipment and supplies will be required:

- Supply of thermal conducting paste such as Omegatherm© OB-201
- Two high-accuracy & resolution handheld thermistor thermometer such as Omega HH41
- Two precision thermistor such as Omega ON-409-PP
- Laptop computer with communication cables
- Misting Bottle for cleaning sensor and pavement surface and for applying films
- Dry cloths or paper towels
- Testing and Maintenance Forms

Validation Test 1-1: Pavement Temperature between 32 and 50ºF (Dry Pavement)

Procedures for Testing
To test the pavement sensor for temperature compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 40º F.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Apply a dab of thermal grease to the subject sensor (avoiding the brass pins and depression of the sensor head) and surrounding area such that a thermistor can be affixed (using the grease as an adhesive) to both the subject sensor and surrounding pavement.
5	Affix a thermistor to both the subject sensor head and the pavement surface 2.5 inches from the subject sensor
6	Record the time for future reference.
7	Begin recording the temperature data and then wait for a minimum of 10 minutes.
8	Check temperature data for sensor temperature stability. If stability has not been achieved wait two minutes and recheck. Go to next step after sensor stability has been achieved. **Note:** Stability of the temperature readings occurs when the both thermistors vary less than 0.4º F (0.2º C) between successive readings.
9	Record the time and final stabilized temperature readings.
10	Remove thermistors and wipe the equipment and pavement clean of thermal grease.
11	Using the Infrared temperature measuring units and thermocouples, obtain and record the temperatures of the pavement sensor and the pavement adjacent to the pavement sensor.
12	Record the time for future reference.

Laboratory Validation Test 1-2: Pavement Temperature between 32 and 50ºF (Wet Pavement)

Additional Test Specific Equipment and Supplies

- 1 gallon 40º F tap water

Procedures for Testing

To test the pavement sensor for temperature compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 40º F.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Apply a dab of thermal grease to the subject sensor (avoiding the brass pins and depression of the sensor head) and surrounding area such that a thermistor can be affixed (using the grease as an adhesive) to both the subject sensor and surrounding pavement.
5	Affix a thermistor to both the subject sensor head and the pavement surface 2.5 inches from the subject sensor
6	Mist/Spray a 0.5 mm film of 40º F tap water on the test area (approximately 10”x10”). A feeler gauge or half the thickness of a dime may be used to verify film depth.
6	Record the time for future reference.
7	Begin recording the temperature data and then wait for a minimum of 10 minutes.
8	Check temperature data for sensor temperature stability. If stability has not been achieved wait two minutes and recheck. Go to next step after sensor stability has been achieved. **Note:** Stability of the temperature readings occurs when the both thermistors vary less than 0.4º F (0.2º C) between successive readings.
9	Record the time and final stabilized temperature readings.
10	Remove thermistors and wipe the equipment and pavement clean of thermal grease.
11	Using the Infrared temperature measuring units and thermocouples, obtain and record the temperatures of the pavement sensor and the pavement adjacent to the pavement sensor.
12	Record the time for future reference.

Laboratory Validation Test 1-3: Pavement Temperature at 32º F (Wet Pavement)

Additional Test Specific Equipment and Supplies

- A 10-inch section of 12-inch diameter PVC pipe (or similar)
- 2 gallons of distilled water
- 2 pounds of crushed ice made from distilled water

Procedures for Testing

To test the pavement sensor for temperature compliance, perform the following steps:

Step	**Action**
1	Stabilize the pavement test sections in the testing chamber at 40º F.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Apply silicone paste in two beads to the bottom edge of the PVC pipe and press the pasted edge of the pipe onto the pavement so that there is a watertight seal between the PVC pipe and pavement. Apply a bead of silicone to the inside edge of the pipe to further reinforce the seal between the pipe section and the pavement.
5	Fill the PVC pipe with one gallon of distilled water and ice mixture to form an ice bath, Gently stir the ice bath for a minimum of 10 minutes.
6	Place thermistor in center of ice bath so that it can measure the temperature of the ice bath.
7	Record the time for future reference.
8	Begin recording the temperature data.
9	Check temperature data for sensor temperature stability. If stability has not been achieved wait 2 minutes and recheck. Go to step 10 after sensor stability has been achieved. **Note:** Stability of the temperature readings occurs when the both thermistors vary less than 0.4º F (0.2º C) between successive readings.
10	Record the time and final stabilized temperature readings.
11	Remove the PVC pipe and thermistors and wipe the equipment and pavement clean of thermal grease.
12	Using the Infrared temperature measuring unit, obtain and record the temperatures of the pavement sensor and the pavement adjacent to the pavement sensor.

Step	Action
13	Record the time for future reference. Complete the Testing and Maintenance Form.
14	Disconnect computer equipment.
15	Fill out Validation Test Form.

Laboratory Validation Test 1-4: Pavement Temperature Forced Below 32º F (Dry Pavement)

Additional Test Specific Equipment and Supplies

- 2 pounds of dry ice and cooler

Procedures for Testing

To test the pavement sensor for temperature compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 32º F.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Apply thermal grease to the subject sensor (avoiding the brass pins and depression of the sensor head) and surrounding area such that a thermistor can be affixed (using the grease as an adhesive) to both the subject sensor and surrounding pavement.
5	Affix a thermistor to each, the subject sensor head and the pavement surface 2.5 inches from the subject sensor
6	Apply dry ice to and around the test area (approximately 10"x10")
8	Record the time for future reference.
11a	Begin recording the temperature data. Wait for a minimum of 10 minutes.
11b	Check temperature data for sensor temperature stability (refer to section 4.4 for sensor temperature stability definition). If stability has not been achieved wait two minutes and recheck. Go to step 12 after sensor stability has been achieved. **Note:** Stability of the temperature readings occurs when the both thermistors vary less than 0.4º F (0.2º C) between successive readings.
12	Record the time and final stabilized temperature readings.
13	Wipe the equipment and pavement clean of thermal grease.
14	Using the infrared temperature measuring unit, obtain and record the temperatures of the pavement sensor and the pavement adjacent to the pavement sensor.
15	Record the time for future reference. Complete the Testing and Maintenance Form.

Step	Action
16	Disconnect computer equipment.
17	Fill out Validation Test Form.

Laboratory Validation Test 1-5: Pavement Temperature Forced Below 32º F (Wet Pavement)

Additional Test Specific Equipment and Supplies

- A 10-inch section of 12-inch diameter PVC pipe (or similar)
- 2 gallons of a saturated salt brine solution
- 3 pounds of ice

Procedures for Testing

To test the pavement sensor for temperature compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 40º F.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Apply silicone paste in two beads to the bottom edge of the PVC pipe and press the pasted edge of the pipe onto the pavement so that there is a watertight seal between the PVC pipe and pavement. Apply a bead of silicone to the inside edge of the pipe to further reinforce the seal between the pipe section and the pavement.
5	Fill the PVC pipe with an ice and brine mixture to form an ice bath, Gently stir the ice bath for a minimum of 10 minutes.
6	Place thermistor in center of ice bath so that it can measure the temperature of the ice bath.
7	Record the time for future reference.
8	Begin recording the temperature data.
9	Check temperature data for sensor temperature stability. If stability has not been achieved wait 2 minutes and recheck. Go to step 10 after sensor stability has been achieved. **Note:** Stability of the temperature readings occurs when the both thermistors vary less than 0.4º F (0.2º C) between successive readings.
10	Record the time and final stabilized temperature readings.
11	Remove the PVC pipe and thermistors and wipe the equipment and pavement clean of thermal grease.
12	Using the Infrared temperature measuring unit, obtain and record the temperatures of the pavement sensor and the pavement adjacent to the pavement sensor.

Step	Action
13	Record the time for future reference. Complete the Testing and Maintenance Form.
14	Fill out Validation Test Form.

Laboratory Validation Test 1-6: Pavement Temperature below 25º F (Dry Pavement)

Procedures for Testing

To test the pavement sensor for temperature compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 20º F.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Apply a dab of thermal grease to the subject sensor (avoiding the brass pins and depression of the sensor head) and surrounding area such that a thermistor can be affixed (using the grease as an adhesive) to both the subject sensor and surrounding pavement.
5	Affix a thermistor to both the subject sensor head and the pavement surface 2.5 inches from the subject sensor
6	Record the time for future reference.
7	Begin recording the temperature data and then wait for a minimum of 10 minutes.
8	Check temperature data for sensor temperature stability. If stability has not been achieved wait two minutes and recheck. Go to next step after sensor stability has been achieved. **Note:** Stability of the temperature readings occurs when the both thermistors vary less than 0.4º F (0.2º C) between successive readings.
9	Record the time and final stabilized temperature readings.
10	Remove thermistors and wipe the equipment and pavement clean of thermal grease.
11	Using the Infrared temperature measuring units and thermocouples, obtain and record the temperatures of the pavement sensor and the pavement adjacent to the pavement sensor.
12	Record the time for future reference.

LABORATORY VALIDATION TEST PLAN 2: PAVEMENT SURFACE MOISTURE CONDITION

The goal of Validation Test Plan 2 is to validate the field test procedures for determining whether the pavement sensor is accurately monitoring the pavement moisture condition (dry, wet, freezing or frost).

Validation Test 2-1: Dry Condition

Additional Test Specific Equipment and Supplies

- A brass brush to clean the pins on top of the sensor.

Procedures for Testing

To test the pavement sensor for surface state compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 40º F.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Make a visual observation of the pavement sensor's physical condition.
5	After sensor surface condition has been updated on the computer, obtain the moisture condition output from the computer and record the condition.
6	Record the time for future reference.

Laboratory Validation Test 2-2: Wet Condition

Additional Test Specific Equipment and Supplies

- 1 gallon of 40º F tap water
- A brass brush to clean the pins on top of the sensor.

Procedures for Testing

To test the pavement sensor for surface state compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 40º F.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Mist/spray a 0.5 mm film of 40º F tap water on the test area (approximately 10"x10"). A feeler gauge or half the thickness of a dime may be used to verify film depth.
4	Make a visual observation of the pavement sensor's physical condition.
5	After sensor surface condition has been updated on the computer, obtain the moisture condition output from the computer and record the condition.
6	Record the time for future reference.

Laboratory Validation Test 2-3: Freezing Condition (Pavement below 25º F)

Additional Test Specific Equipment and Supplies

- 1 gallon of 40º F tap water
- A brass brush to clean the pins on top of the sensor.

Procedures for Testing

To test the pavement sensor for surface state compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 20º F. Refer to section 4.4 for definition of pavement temperature stabilization.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Connect the computer to the subject sensor RPU so that the pavement surface moisture condition is displayed.
5	Make a visual observation of the pavement sensor's moisture condition.
6	Record the reported moisture and visual observation on the Testing and Maintenance Form.
7	Record the time for future reference.
8	Clean the top of the pavement sensor with a dry cloth. Clean the metal contact pins on the surface of sensor with a brass brush (if applicable).
9a	Mist/Spray 40º F tap water on the test area (approximately 10"x10").
9b	Wait for the water to freeze.
10	Again, observe and record the visual moisture condition and displayed pavement moisture condition.
11	Record the time for future reference.

Laboratory Validation Test 2-4: Frost Condition

Additional Test Specific Equipment and Supplies

- Large open container or cooler to hold water
- Large supply of hot (approximately 170º F) tap water
- Instruments to measure dew point temperature and humidity.

Procedures for Testing

To test the pavement sensor for surface state compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at -20º F. Refer to section 4.4 for definition of pavement temperature stabilization.
2	Record the time for future reference.
3	Clean and dry the subject sensor and surrounding 1 by 1 foot area using a dry cloth.
4	Connect the computer to the subject sensor RPU so that the pavement surface moisture condition is displayed.
5	Record the time for future reference.
7	Place the large container filled with hot water into the test chamber. This is done to raise the humidity of the test chamber to enable the formation of frost.
8	Vigorously stir the water until frost is visible on the pavement and sensor surface.
9	Record the moisture condition reported by the sensor on the Testing and Maintenance Form.
10	Record the time for future reference. Fill out Validation Test Form.

VALIDATION TEST PLAN 3: DETERMINATION OF CHEMICAL CONCENTRATION/PAVEMENT FREEZE POINT

The goal of Validation Test Plan 3 is to validate the field test procedures for determining whether the pavement sensor is accurately monitoring the freezing point of the pavement, taking into account the residual de-icing chemical on the road surface. Although both sodium chloride and magnesium chloride brines are commonly used in the field, this study will only focus on the sodium chloride brine due to the test sensor software configuration. Four concentrations will be evaluated: 4%, 10%, 15% and 23%.

Laboratory Validation Test 3-1: Testing Various Concentration of Chemical Brine Solutions on Passive Sensors

Additional Test Specific Equipment and Supplies

- A brass brush to clean the pins on top of the sensor.
- 2 gallons of distilled water
- 1 quart of each brine concentration

Procedures for Testing

To test the pavement sensor for freezing point compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 30º F.
2	Record the time for future reference.
3	Connect the computer to the subject sensor RPU so that the pavement freezing temperature is displayed.
4	Clean the tops of the sensor pins using a brass brush.
5	Clean the sensor surface by liberally applying distilled water and then wiping dry with a clean rag three times.
6	Mist/spray a 0.5 mm film of 40º F tap water on the test area (approximately 10"x10"). A feeler gauge or half the thickness of a dime may be used to verify film depth..
7	Record the time for future reference.
8	Check freezing point data for freeze point. If stability has not been achieved wait 2 minutes and recheck. Proceed when stability has been reached.
9	Record the time and final stabilized freezing point readings. Complete the Testing and Maintenance Form.

Step	Action
10	Repeat steps 5 to 10 for the next most concentrated brine solution.
11	Record the time for future reference. Fill out Validation Test Form.

Laboratory Validation Test 3-2: Testing Various Concentration of Chemical Brine Solutions on Active Sensors

Additional Test Specific Equipment and Supplies

- A brass brush to clean the pins on top of the sensor.
- 2 gallons of distilled water
- 1 quart of each brine concentration

Procedures for Testing

To test the pavement sensor for freezing point compliance, perform the following steps:

Step	Action
1	Stabilize the pavement test sections in the testing chamber at 30º F.
2	Record the time for future reference.
3	Connect the computer to the subject sensor RPU so that the pavement freezing temperature is displayed.
4	Clean the tops of the sensor pins using a brass brush.
5	Clean the sensor surface by liberally applying distilled water and then wiping dry with a clean rag three times.
6	Mist/spray a 0.5 mm film of 40º F tap water on the active sensor and surrounding 10”x10” area. A feeler gauge or half the thickness of a dime may be used to verify film depth.
7	Record the time for future reference.
8	Record data every 12 minutes for a minimum of 36 minutes.
9	Record the time and final stabilized freezing point readings. Complete the Testing and Maintenance Form.
10	Record the time for future reference and repeat steps 5 to 10 for the next most concentrated brine solution.
11	Record the time for future reference. Fill out Validation Test Form.

REFERENCES

1. Burtwell, Marilyn, "Assessment of Road Surface Freezing Point Sensors for the UK." Preprint for the Xth PIARC International Winter Road Congress in Lulea, Sweden. (1998) pp. 767-778.

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APPENDIX G
VALIDATION TEST FINDINGS

This section contains laboratory results for the Validation Test Plan. The first section focuses on Validation Test Plan 1 and contains primarily graphs and data to show the findings of the temperature tests. Some graphs show trends that emerged from running the tests as shown in the validation test plan. Please refer to the Validation Test Interpretations for further details on what was changed in the laboratory validation testing.

The names of the vendors of the sensors used in this portion of the project have been removed in this section. The graphs show examples of phenomena that were found in the laboratory testing and generally apply to all sensors.

Validation Test Plan 1

The following pages contain graphs and data tables for tests run in the laboratory for Test Plan 1. It should be noted that many of these graphs are included to illustrate some of the limitations of some of the sensors. Annotated graphs are especially important in showing some of the complications that were found in laboratory testing. One such complication is that the subsurface sensors such as Point Six's sensor did not respond to the ice bath. This is shown in Figure H-13. For more detail regarding these issues, please see the interpretations that correspond with that test.

Test Duration

While the laboratory tests were run, time was kept to determine how long each test would take. The total test durations were averaged and rounded to the nearest five minute interval. A summary of test durations may be found in table G-1.

Table G-1. Table Laboratory Test Durations

Validation Test Plan 1: Determination of Pavement Surface Temperature	
Validation Test 1-1	20 minutes
Validation Test 1-2	25 minutes
Validation Test 1-3	45 minutes
Validation Test 1-4	30 minutes
Validation Test 1-5	45 minutes
Validation Test 1-6	20 minutes
Validation Test Plan 2: Evaluation of Surface Moisture Conditions	
Validation Test 2-1	10 minutes
Validation Test 2-2	10 minutes
Validation Test 2-3	20 minutes
Validation Test 2-4	**N/A**
Validation Test Plan 3: Determination of Chemical Freezing Point	
Validation Test 3-1	15 minutes
Validation Test 3-2	30 minutes

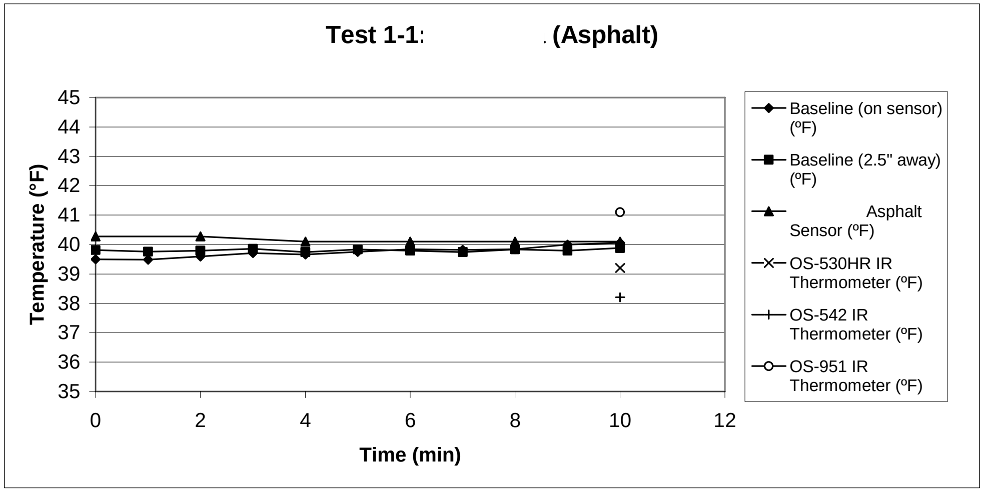
Test 1-1 (40ºF, Dry): (Asphalt and Concrete)

Vendor:
Material: **Asphalt**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Asphalt Sensor (ºF)
0	39.50	39.81	40.28
1	39.48	39.76	
2	39.59	39.79	40.28
3	39.71	39.85	
4	39.66	39.74	40.10
5	39.75	39.83	
6	39.84	39.79	40.10
7	39.82	39.74	
8	39.84	39.83	40.10
9	40.00	39.79	
10	40.06	39.88	40.10

Other Baselines

	OS-530HR (ºF)	OS-542 (ºF)	OS-951 (ºF)
On Sensor	39.2	38.2	41.1
2.5" Away	39.3	39.2	41.3



Material: **Concrete**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Concrete Sensor (ºF)
0	40.52	40.58	40.26
1	40.41	40.58	
2	40.52	40.67	40.26
3	40.57	40.71	
4	40.26	40.44	40.26
5	40.43	40.71	
6	40.57	40.85	40.26
7	40.43	40.67	
8	40.43	40.62	40.26
9	40.61	40.85	
10	40.57	40.80	40.26

Other Baselines

	OS-530HR (ºF)	OS-542 (ºF)	OS-951 (ºF)
On Sensor	40.4	41.4	43.0
2.5" Away	40.5	42.4	42.5

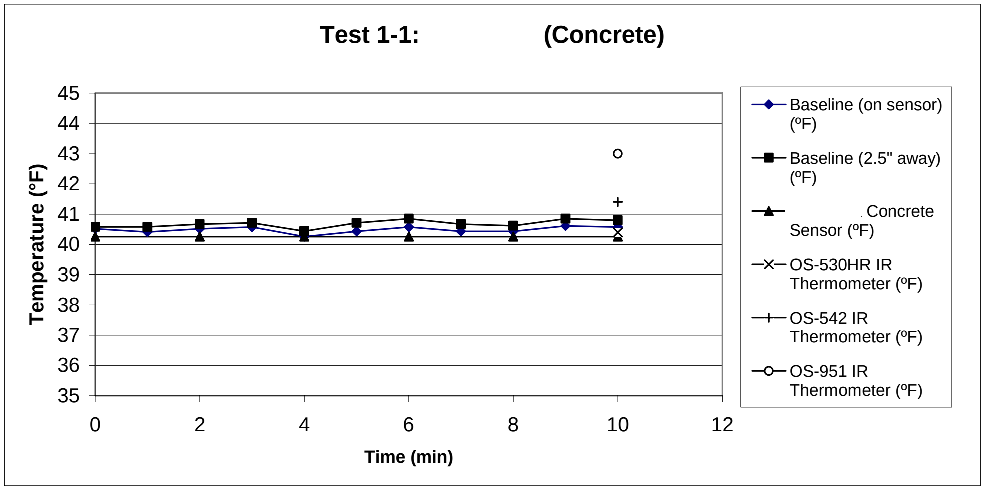


Figure G-1

Test 1-1 (40ºF, Dry): (Asphalt)

Vendor:
Material: **Asphalt**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Asphalt Sensor (ºF)
0	40.44	40.12	39.9
1	40.44	40.10	39.9
2	40.44	40.12	39.9
3	40.51	40.14	39.9
4	40.30	39.85	39.9
5	40.42	40.03	39.9
6	40.42	39.99	39.9
7	40.55	40.14	39.9
8	40.71	40.39	39.9
9	40.33	40.03	40.1
10	40.44	40.12	39.9

Other Baselines

	OS-530HR (ºF)	Omegaette (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	36.4	39.9	40.4	40.2
2.5" Away	37.3	39.8	40.1	42.2

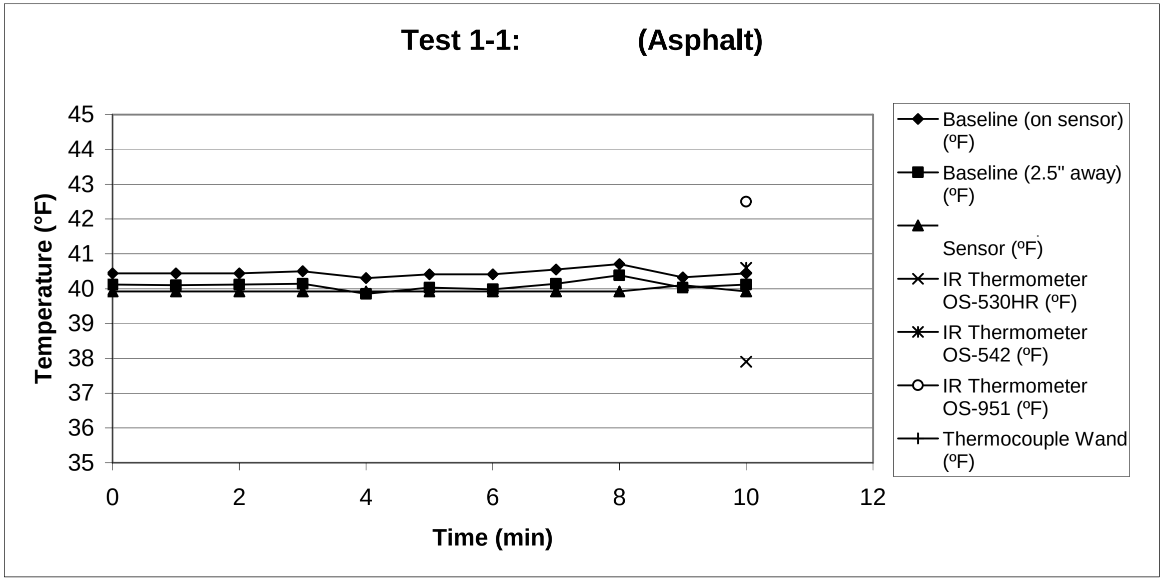


Figure G-2

Test 1-1 (40ºF, Dry): (Concrete)

Vendor:
Material: **Concrete**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Asphalt Sensor (ºF)
0	39.48	40.68	39.4
1	39.48	40.55	
2	39.57	40.61	39.3
3	39.71	40.73	
4	39.78	40.66	39.5
5	39.71	40.46	
6	39.75	40.59	39.5
7	39.66	40.39	
8	39.71	40.46	39.4
9	39.71	40.44	
10	39.78	40.35	39.5

Other Baselines

	OS-530HR (ºF)	Omegaette (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	37.9	40.6	42.5	32.6
2.5" Away	37.2	41.1	42.0	40.6

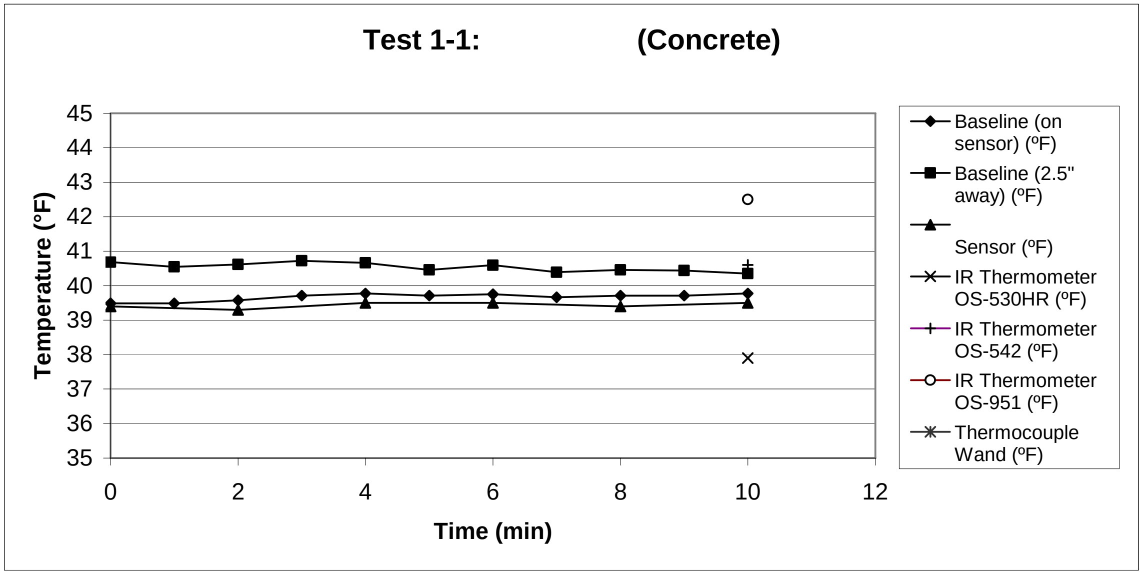


Figure G-3

Test 1-2 (40ºF, 0.5 mm Film): (Asphalt)

Vendor:
Material: **Asphalt**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Asphalt Sensor (ºF)
0	40.30	39.72	40.1
1	40.60	40.03	40.1
2	40.33	39.76	40.1
3	40.64	40.21	40.1
4	40.46	39.87	39.9
5	40.51	39.94	40.1
6	40.35	39.76	40.1
7	40.37	39.72	40.1
8	40.48	39.94	40.1
9	40.37	39.76	40.1
10	40.28	39.58	40.1
11	40.42	39.85	40.1

Other Baselines

	OS-530HR (ºF)	OS-542 (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	37.4	40.4	40.6	42.3
2.5" Away	37.2	40.4	40.7	40.5

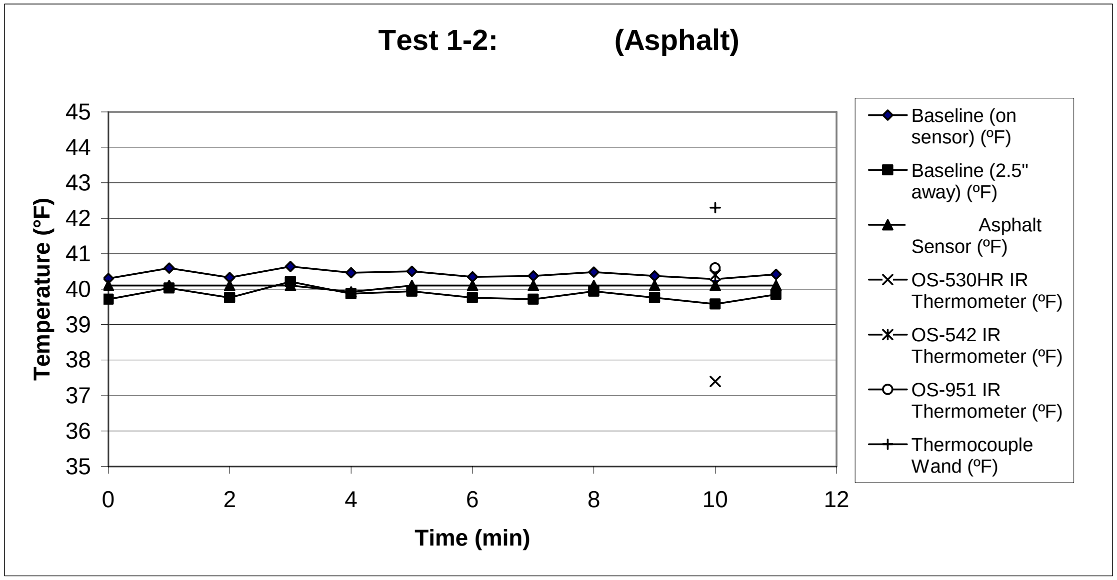


Figure G-4

Test 1-2 (40ºF, 0.5 mm Film): (Concrete)

Vendor:
Material: **Concrete**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Asphalt Sensor (ºF)
0	39.95	41.57	41.6
1	39.95	40.70	
2	39.66	40.17	41.0
3	39.60	39.86	
4	39.78	39.95	40.5
5	39.62	39.74	
6	39.71	39.77	40.2
7	39.66	39.72	
8	39.93	39.95	40.1
9	39.75	39.72	
10	40.07	40.03	40.1
11	39.87	39.88	
12	39.87	39.95	39.9
13	39.75	39.65	
14	39.75	39.63	40.0
15	39.87	39.86	
16	39.75	39.63	40.0
17	39.66	39.59	
18	39.78	39.70	39.9

Other Baselines

	OS-530HR (ºF)	OS-542 (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	38.0	41.6	42.6	33.4
2.5" Away	37.7	41.6	42.4	40.8

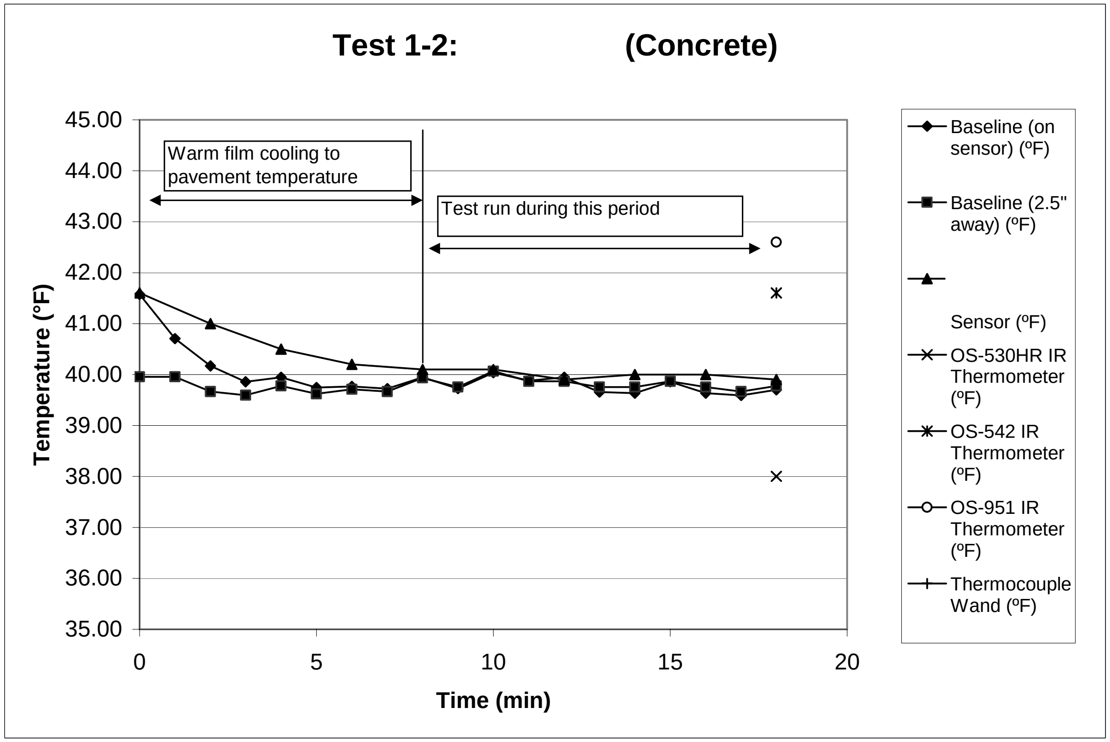


Figure G-5

Test 1-3 (40ºF, Distilled Water Ice Bath): (Asphalt)

Vendor:
Material: Asphalt

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Asphalt Sensor (ºF)
0	34.02	33.97	33.9
1	34.14	34.11	
2	34.18	34.22	34.2
3	34.25	34.31	
4	34.32	34.42	34.3
5	34.41	34.42	
6	34.43	34.51	34.5
7	34.50	34.60	
8	34.56	34.69	34.5
9	34.59	34.73	
10	34.70	34.82	34.9
11	34.70	34.85	
12	34.70	34.93	34.9
13	34.74	34.93	
14	34.79	35.00	34.8
15	34.81	35.02	
16	34.88	35.11	35.1
17	34.88	35.11	
18	34.90	35.14	35.1
19	34.94	35.23	
20	34.94	35.23	35.0
21	34.99	35.23	
22	34.99	35.29	35.1
23	34.99	35.29	

Other Baselines

	OS-530HR (ºF)	Omegaette (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	36.1	38.2	38.0	41.1
2.5" Away	36.2	38.2	38.2	41.0

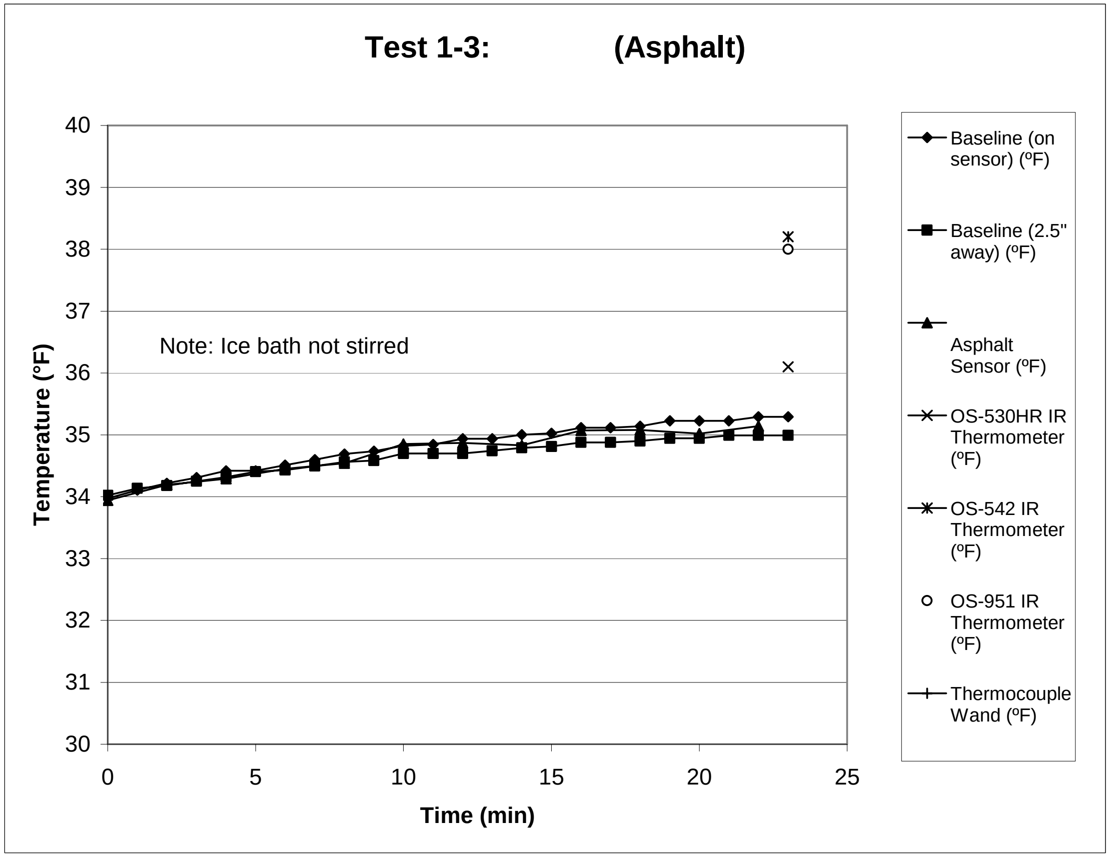


Figure G-6

Test 1-3, Constantly Stirred Ice Bath: (Concrete)

Vendor:
Material: **Concrete**

Time (min)	Concrete Sensor (ºF)
0	38.5
2	38.4
4	35.9
6	33.3
8	32.9
10	32.6
12	32.6
14	32.5
16	32.4
18	32.4
20	32.2
22	32.1
24	32.2
26	32.1
28	32.1

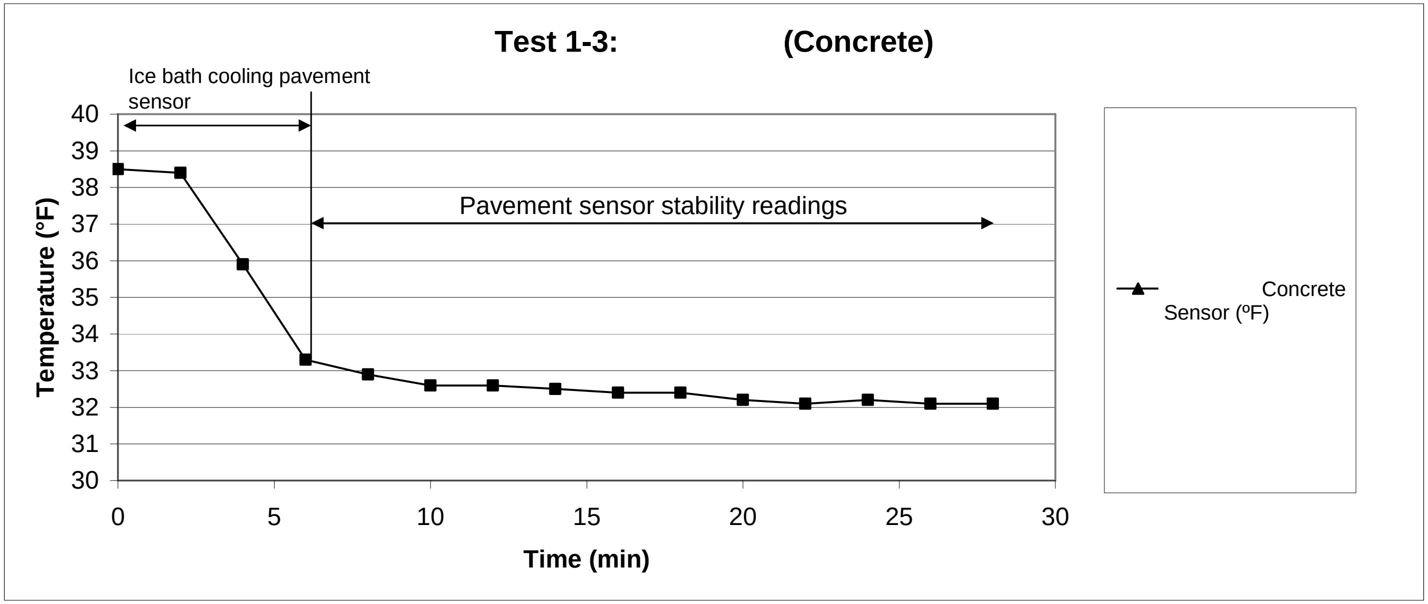
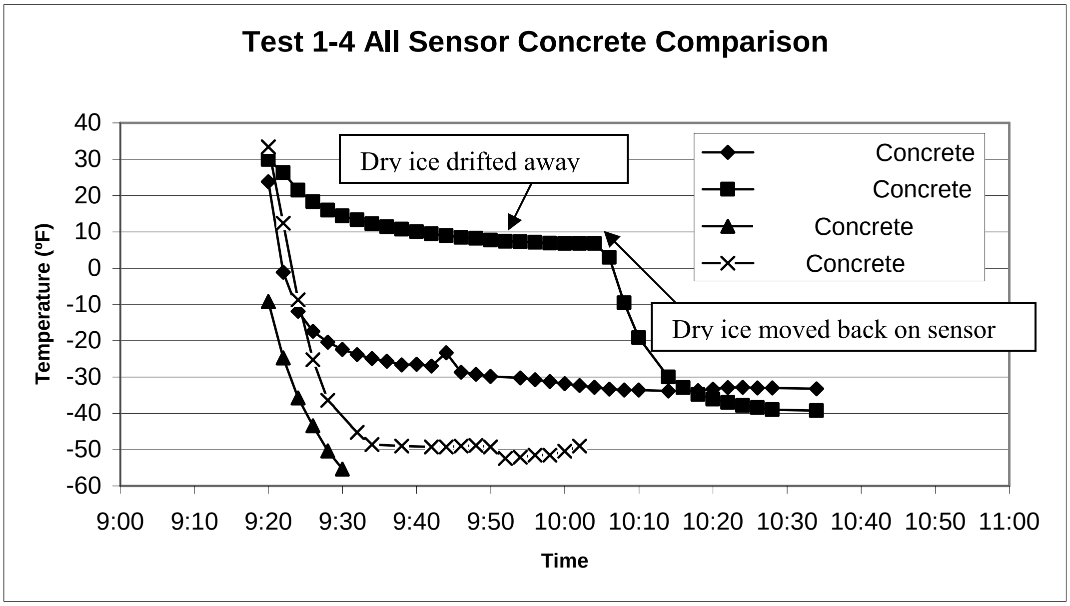
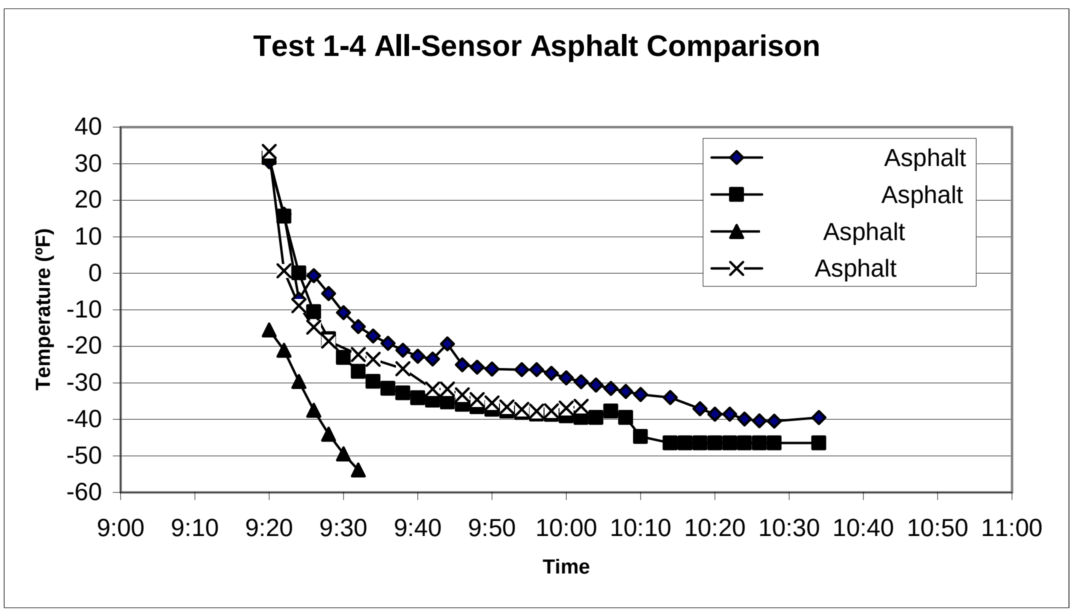


Figure G-7





Figures G-8 and G-9. Comparison of sensor readings after dry ice was applied to sensor surface.

Table G-2

Test 1-4 (Dry Ice)

***All temperatures in degrees Fahrenheit**

	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt
9:20	23.8	30.5	29.9	31.6	-9.2	-15.5	33.4	33.4
9:22	-1.1	16.2	26.3	15.6	-24.7	-21.1	12.4	0.7
9:24	-11.9	-7.1	21.5	0.1	-35.7	-29.6	-8.7	-8.9
9:26	-17.4	-0.7	18.3	-10.5	-43.4	-37.5	-25.2	-14.8
9:28	-20.4	-5.6	16.0	-17.9	-50.3	-44.1	-36.4	-18.6
9:30	-22.4	-10.8	14.4	-23.1	-55.3	-49.5		
9:32	-23.8	-14.6	13.3	-26.9		-53.9	-45.2	-22.2
9:34	-24.9	-17.2	12.2	-29.6			-48.6	-23.6
9:36	-25.6	-19.2	11.4	-31.5				
9:38	-26.6	-21.1	10.7	-32.8			-49.0	-26.1
9:40	-26.5	-22.7	10.1	-34.1				
9:42	-27.0	-23.5	9.5	-34.8			-49.2	-31.7
9:44	-23.3	-19.3	9.0	-35.3			-49.2	-31.7
9:46	-28.6	-25.1	8.5	-35.9			-49.0	-33.3
9:48	-29.2	-25.7	8.2	-36.6			-48.8	-34.6
9:50	-29.8	-26.2	7.7	-37.3			-49.2	-35.5
9:52			7.4	-37.8			-52.4	-36.6
9:54	-30.2	-26.4	7.3	-38.2			-52.1	-37.3
9:56	-30.7	-26.4	7.1	-38.6			-51.5	-37.8
9:58	-31.2	-27.4	6.9	-38.7			-51.5	-37.7
10:00	-31.8	-28.6	6.8	-39.1			-50.4	-36.9
10:02	-32.3	-29.7	6.8	-39.5			-49.0	-36.4
10:04	-32.8	-30.6	6.8	-39.5				
10:06	-33.3	-31.5	3.0	-37.8				
10:08	-33.6	-32.4	-9.5	-39.5				
10:10	-33.6	-33.2	-19.1	-44.7				
10:12								
10:14	-33.8	-34.0	-30.0	-46.5				
10:16			-32.9	-46.5				
10:18	-33.7	-37.1	-34.8	-46.5				
10:20	-33.3	-38.6	-36.1	-46.5				
10:22	-32.9	-38.6	-37.0	-46.5				
10:24	-32.8	-39.9	-37.8	-46.5				
10:26	-33.0	-40.4	-38.4	-46.5				
10:28	-33.0	-40.5	-39.0	-46.5				
10:30								
10:32								
10:34	-33.2	-39.5	-39.2	-46.5				

Test 1-5 (40ºF, Saturated NaCl Bath): (Concrete)

Vendor:
Material: **Concrete**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Concrete Sensor (ºF)
0	17.64	18.46	19.0
1	17.98	18.37	18.9
2	18.15	18.41	
3	18.13	18.39	18.7
4	18.27	18.39	18.5
5	18.15	18.32	18.5
6	18.35	18.41	
7	18.25	18.51	
8	18.44	18.68	18.5
9	18.49	18.51	18.5
10	18.73	18.71	18.5
11	18.69	18.88	18.5
12	18.59	18.88	
13	18.85	18.85	18.5
14	18.93	18.95	
15	19.00	18.73	
16	18.88	19.00	
17	19.00	18.92	
18	18.83	19.17	
19	18.88	19.00	
20	18.98	19.02	
21	18.81	19.07	18.9

Other Baselines

	OS-530HR (ºF)	Omegaette (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	25.0	28.0	28.2	29.2
2.5" Away	24.4	26.6	27.1	27.1

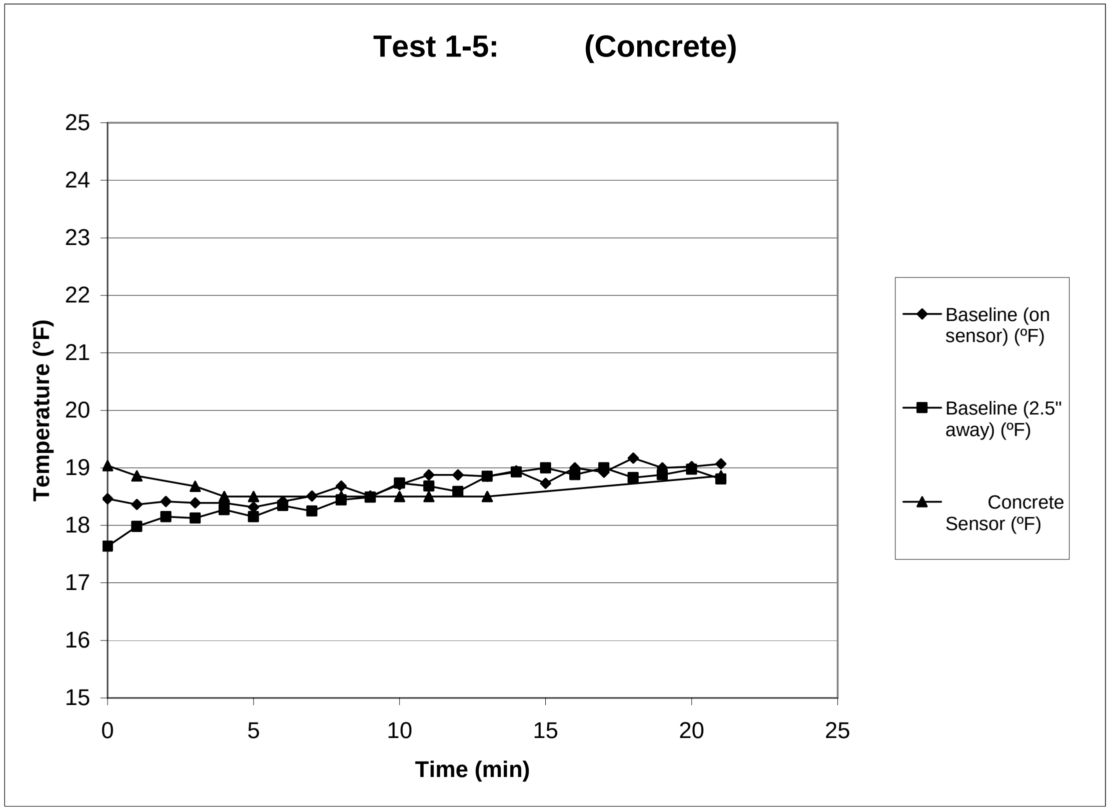


Figure G-10

Test 1-5 (40ºF, Saturated NaCl Bath): (Asphalt)

Vendor:
Material: **Asphalt**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Asphalt Sensor (ºF)
0	27.49	27.36	31.7
1	26.66	26.51	31.7
2	26.38	26.08	31.7
3	25.85	25.61	31.7
4	25.59	25.11	31.7
5	25.08	24.55	31.7
6	24.71	24.50	31.7
7	24.57	24.50	31.7
8	24.52	24.29	31.7
9	24.28	24.27	31.7
10	24.14	23.94	31.7

Other Baselines

	OS-530HR (ºF)	Omegaette (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	25.5	31.0	28.8	29.7
2.5" Away	25.3	31.0	29.4	28.9

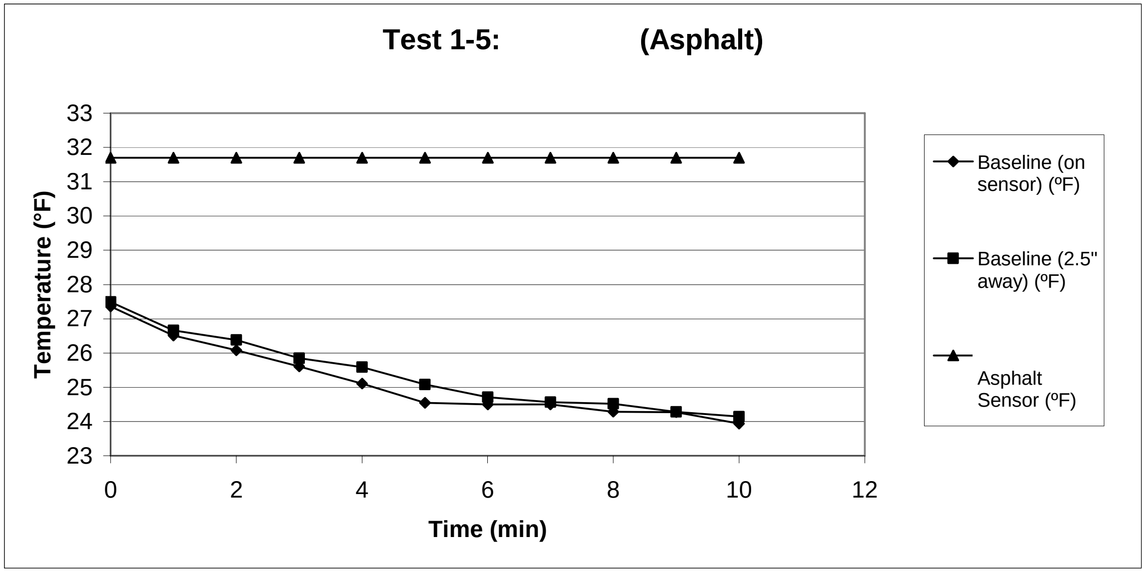


Figure G-11

Test 1-5 (40ºF, Saturated NaCl Bath): (Concrete)

Vendor:
Material: **Concrete**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Concrete Sensor (ºF)
0	26.4	26.4	25.0
1	25.2	25.8	24.6
2	24.6	25.3	24.4
3	23.9	25.0	24.1
4	23.5	24.6	23.9
5	23.3	24.3	23.7
6	23.0	24.0	23.5
7	22.7	24.1	23.4
8	22.6	23.8	23.2
9	22.4	23.8	23.0
10	22.3	23.5	22.8
11	22.2	23.5	22.8
12	22.1	23.3	22.6
13	21.9	23.3	22.6
14	21.9	23.3	22.5
15	21.8	23.2	22.5
16	21.6	23.1	22.3
17	21.5	23.1	22.1
18	21.4	23.0	22.1
19	21.3	22.9	21.6
20	21.3	22.9	21.7
21	21.3	22.9	21.7
22	21.2	22.8	21.9
23	21.1	22.8	21.9
24	21.1	22.7	21.9
25	21.0	22.7	21.9

Other Baselines

	OS-530HR (ºF)	Omegaette (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	26.3	29.8	28.7	29.3
2.5" Away	26.1	28.4	28.3	28.3

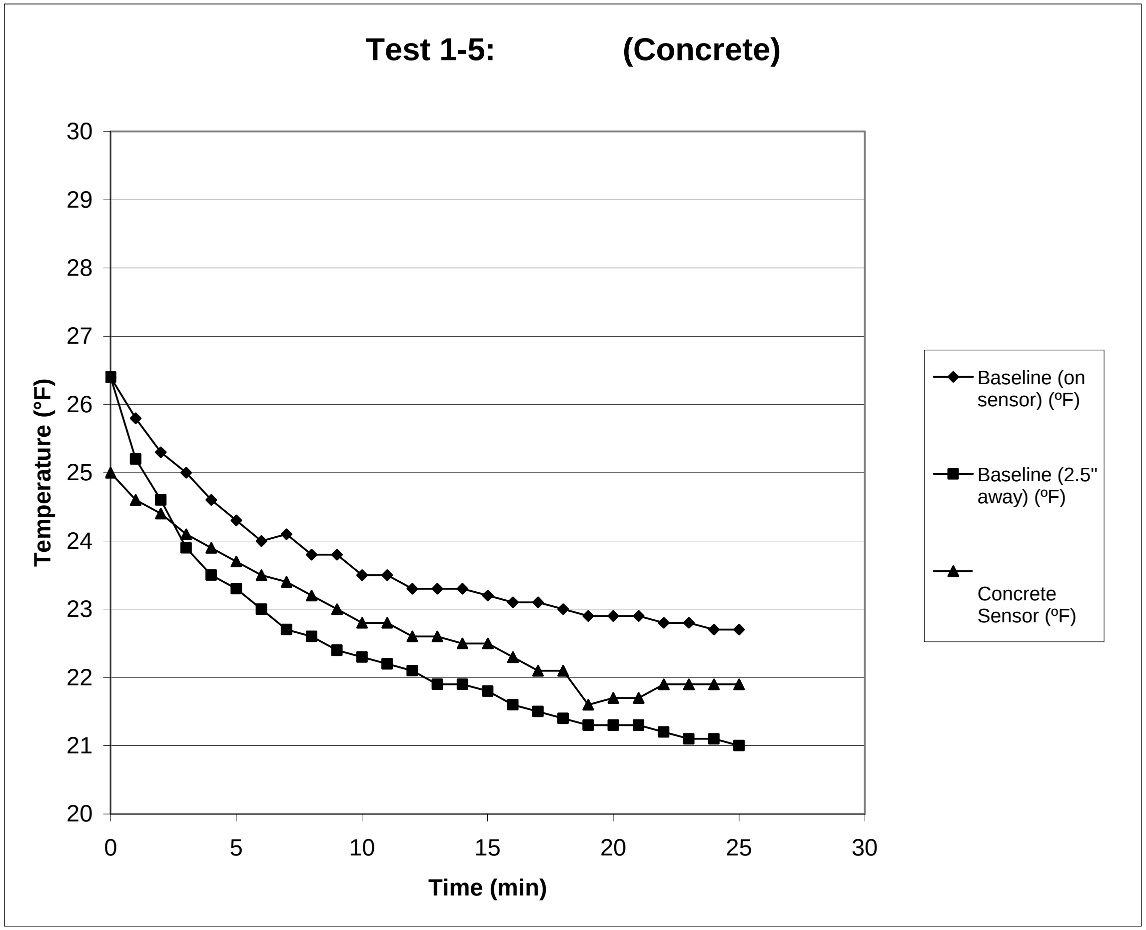


Figure G-12

Test 1-5 (40ºF, Saturated NaCl Bath): (Asphalt)

Vendor:
Material: **Asphalt**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Asphalt Sensor (ºF)
0	24.94	27.41	33.3
1	25.04	27.50	
2	25.04	27.43	32.0
3	25.13	27.50	
4	25.04	27.64	30.4
5	24.76	27.46	
6	24.55	27.62	29.8
7	24.27	27.62	
8	24.34	27.55	
9	24.08	27.02	
10	23.82	27.11	
11	23.80	27.02	
12	23.71	26.37	28.6
13	23.59	26.40	
14	23.43	26.28	
15	23.19	25.79	
16	23.24	25.77	28.3
17	23.03	25.35	
18	23.03	25.84	27.8
19	22.82	25.45	
20	22.79	25.17	27.6
21	22.72	25.40	
22	22.65	25.03	27.3
23	22.39	24.89	
24	22.53	24.96	27.1
25	22.44	24.91	
26	22.46	25.05	27.1
27	22.37	25.03	
28	22.32	25.00	27.0
29	22.27	25.00	
30	22.27	24.91	27.0
31	22.30	24.75	
32	22.34	24.72	26.8
33	22.32	24.84	
34	22.20	24.96	26.8

Other Baselines

	OS-530HR (ºF)	Omegaette (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	25.0	28.0	28.2	29.2
2.5" Away	24.4	26.6	27.1	27.1

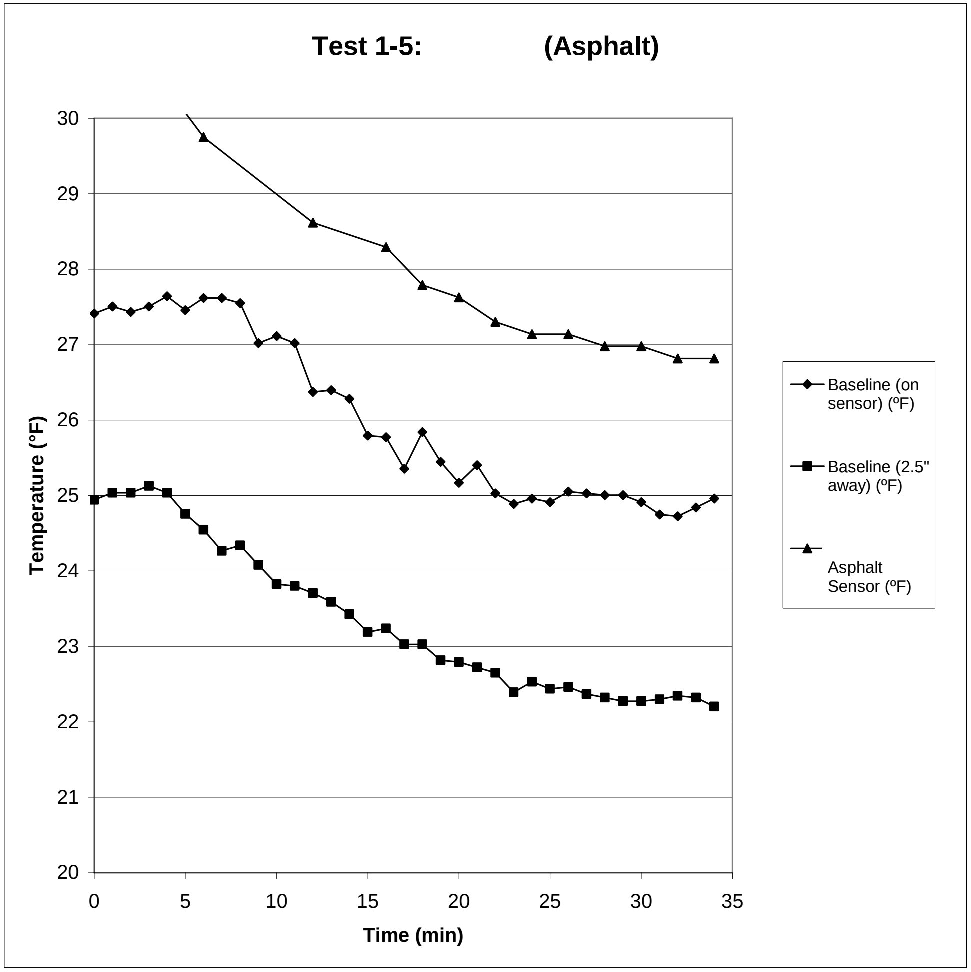


Figure G-13

Test 1-6 (20ºF, Dry): (Concrete)

Vendor:
Material: **Concrete**

Time (min)	Baseline (on sensor) (ºF)	Baseline (2.5" away) (ºF)	Concrete Sensor (ºF)
0	25.56	26.18	26.33
1	25.40	26.02	26.33
2	25.42	25.81	
3	25.37	25.78	26.17
4	25.33	25.81	
5	25.37	25.78	
6	25.23	25.64	
7	25.21	25.63	26.01
8	25.21	25.72	
9	25.21	25.59	
10	25.23	25.65	
11	25.19	25.68	
12	25.16	25.53	
13	25.16	25.57	25.84
14	25.16	25.62	
15	25.07	25.55	
16	25.07	25.53	
17	25.09	25.51	
18	25.07	25.53	
19	24.98	25.37	25.68

Other Baselines

	OS-530HR (ºF)	OS-542 (ºF)	OS-951 (ºF)	Wand TC (ºF)
On Sensor	27.9	33.6	LO A	25.7
2.5" Away	27.1	33.8	LO A	25.5

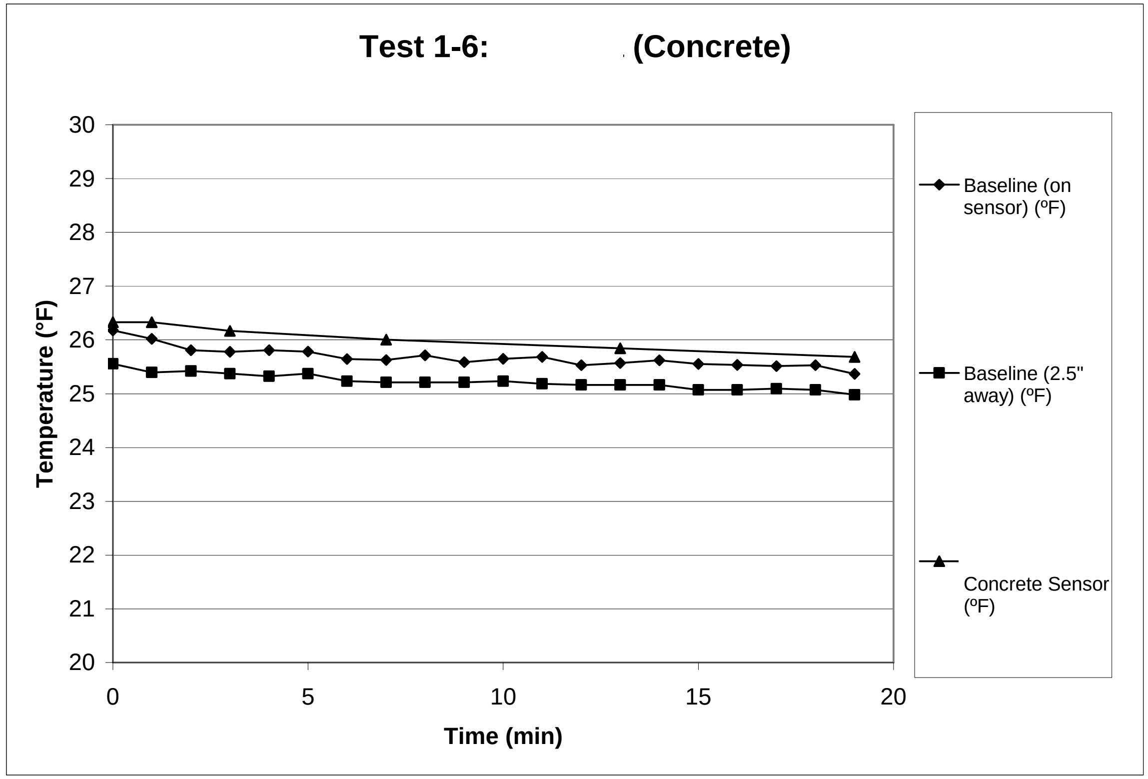


Figure G-15

Validation Test Plan 2

This test plan was designed to find the capabilities of surface state readings of the pavement sensors. For the most part, the sensors read the surface state using the methods stated in the preliminary version of the Validation Test Plan. Although most sensors can detect surface state conditions, the RPU and sensor must be properly set up. Of the sensors that were properly set up, all properly reported dry and wet conditions as specified in Tests 2-1 and 2-2 respectively. In addition, these sensors reported the new condition within two to six minutes.

In addition, Test 2-3 measured the ability of the sensor to detect ice. Of the sensors, only two sensors were properly connected to detect these conditions. One sensor can detect conditions, but was not properly set up to do this. It was found that another sensor gave an “Ice Warning” reading one cycle or two minutes after applying the water. A second sensor also detected the ice. It gave a reading of “Freezing Humidity” after applying the water and five minutes later gave an “Ice” reading. It was found that at the temperatures that the tests were conducted, the sensors gave proper readings. These tests should be run again in the field in a less controlled environment.

The final surface state test was to detect frost. It was determined that it is difficult to produce frost in the cooling chamber. At the prescribed temperature in the Validation Test Plan, it was found that the hot water warms the chamber enough that frost may not be produced. Additional tests cooled the chamber to -20º and then opened the chamber door to produce frost on the pavement sections. After about thirty minutes, frost was visible on the pavement and sensor surfaces, but the sensors did not give frost readings. One sensor again gave a “Freezing Humidity” while another sensor gave a “Chemically Wet” condition. Frost is very difficult to reproduce in a laboratory setting and is time intensive. Further tests must be done in the field to determine if this test should be recommended.

Validation Test Plan 3

The following tables illustrate the findings of Test 3 for both passive and active sensors. It was found that passive sensors were not very accurate in finding the freezing point of the sodium chloride solution, but did register a freezing point depression.

Table G-3. Test 3 Passive Sensor Summary

Pavement Type	Percent NaCl	Freezing Point of Solution (ºF)	Final Sensor Freezing Point (ºF)	Time to reach Final Freezing Point
Asphalt	10	16.4	N/A	Did not stabilize in 30 minutes
Concrete	10	16.4	N/A	Did not stabilize in 30 minutes
Asphalt	15	13.4	-14.8	4
Concrete	15	13.4	-5.0	4
Asphalt	23	7.8	-14.8	4
Concrete	23	7.8	-14.8	8
Asphalt	4	19.4	29.1	4
Concrete	4	19.4	29.7	4
Concrete	10	16.4	19.9	4
Asphalt	15	13.4	19.9	8
Concrete	15	13.4	19.9	4
Asphalt	23	7.8	25.9	4
Concrete	23	7.8	20.5	4
Concrete	4	19.4	29.0	8
Concrete	10	16.4	28.0	8
Concrete	15	13.4	29.0	4
Concrete	23	7.8	25.0	4

The active sensor performed well in finding the freezing point and in all tested cases found the freezing point within the manufacturer's suggested time period of two cycles.

Table G-4. Test 3 Active Sensor Summary

Pavement Type	Percent NaCl	Freezing Point of Solution (ºF)	Final Sensor Freezing Point (ºF)	Time to reach Final Freezing Point (min)
Concrete	4	19.4	24.5	8
Concrete	10	16.4	16.7	4
Concrete	15	13.4	11.7	24
Concrete	23	7.8	11.6	4

APPENDIX H
FIELD TEST PLAN (FOR STATE VISITS)

Project No. 6-15

TESTING AND CALIBRATION METHODS FOR RWIS SENSORS

FIELD TEST PLAN

Prepared for
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

Version 2.0
April 8, 2005

Prepared by
SRF Consulting Group, Inc.

VERSION HISTORY

Version	Date	Status
1.0	December 13, 2004	Initial Version for Panel Review
1.1	January 5, 2005	Revised Version After SRF Testing
1.2	January 24, 2005	Revised for State Visits
1.3	February 21, 2005	Revised After MN State Visit
1.4	March 21, 2005	Revised After NV State Visit
2.0	April 8, 2005	Revised After PA State Visit

TABLE OF CONTENTS FOR FIELD TEST PLAN

1. INTRODUCTION

This Draft Field Test Plan is the result of research performed under NCHRP Project 6-15, Testing and Calibration Methods for RWIS Sensors, by SRF Consulting Group, Inc. The objective of this research is to develop practical guidelines that will allow state agencies to test the accuracy of in-place Environmental Sensor Station (ESS).

Currently, most transportation agencies using ESS sensors rely on vendor-developed testing methods or they accept the sensor data without regular testing. NCHRP has determined that practical guidelines are needed for testing of ESS sensors to ensure that a sensor is providing an accurate representation of actual conditions at the installed site.

This NCHRP research project is in the process of developing standardized methodologies for field-testing various models of ESS sensors. Thus far, this project has developed, and NCHRP has approved, test protocols, conducted tests and analyzed and documented the results of laboratory tests designed to measure pavement sensor outputs. The basic approach is to use a comparative test between baseline and sensor data for various parameters. This Field Test Plan will define and document a set of standardized test procedures that can be used nationwide.

Three different pavement sensor parameters are included:

- Pavement temperature
- Pavement surface state condition
- Freezing point temperature

Various test procedures were first proposed then evaluated using a laboratory environment where the external variables could be controlled and the tests could be repeatedly run. Results from that evaluation were used to develop the standard field-test procedures that are presented here. Because there are more external variables in the field, some additional equipment is necessary, such as a portable shelter to shade the sensors from solar radiation.

To evaluate the procedures in the Field Test Plan, the project team will travel to three states to train state highway department personnel in use of the Field Test Plan and observe repeated trial test runs using the various procedures. This will provide the project team with on-site feedback on the use of the test procedures.

This project is important to the RWIS community because it provides a basis for quality control of inplace pavement sensors. By conducting quality control procedures on ESS data, agencies may find extreme outliers. When this occurs, these field test procedures could then be used to troubleshoot the problem at the RWIS site.

Also, as new RWIS related projects move forward, a trend is to share RWIS information between agencies. Agencies want to be sure that information that they are providing is accurate. These test procedures can verify the validity of their sensors' data.

2. STATE VISITS

To test these procedures in varied environments, the project team will travel to three states across the country. Three different climates in which to run the test procedures have been chosen. The field evaluation testing will be run in climatic regions representing mountain, plains, and lake effect climates. States were also selected such that different manufacturers' ESS equipment could be tested. With multiple states participating in evaluating the field test plan, the test will have an excellent chance to be successful on a nationwide scale.

The evaluation program is designed so that in each state the training will take half of a day and testing will be conducted over an additional three days per sensor. Each day of field-testing will require a lane closure during the testing period, typically 8 a.m. to 4 p.m. A different operator will perform the tests under project team observation each day (three operators in three days). To ensure that the test procedures leave no room for individual interpretation, the three people will conduct the test procedures independently.

Each operator will be asked to collect ten readings after stability is reached to determine the amount of variation that is inherent in the test procedures. To refine procedure clarity and repeatability, exit interviews will be conducted to see what effect factors such as education and familiarity with technology have on the way the operator conducts the tests. Interview questions are presented in Appendix D. Observation of the operators will also be valuable for determining the variability inherent in the proposed field-testing procedures. The findings will be used to refine the procedures and identify an acceptable range of accuracy for each of the tests.

2.1. State Selection

Preliminary contacts have been made, for the field tests, and preliminary approval has been obtained from Nevada, Pennsylvania and Minnesota. Additional contacts were made to further determine the extent of their participation in the study.

Minnesota was chosen as the first state to run the test procedures because the SRF project team is located in Minneapolis, Minnesota. Before moving forward with training DOT personnel, the project team will first train and observe an SRF engineer running the tests. This preliminary test will be run as closely as possible to the way that the Field Test Plan will be carried out in the state visits. The preliminary tests will be run at the same location as the Minnesota state visit. This preliminary testing may reveal testing complications that can be resolved before the DOT personnel testing takes place.

After successfully completing preliminary training and testing, the project team will conduct the three state visits.

1. Minnesota is classified as a plains state and uses SSI sensors.
2. Nevada is classified a mountain terrain state and uses Vaisala sensors.
3. Pennsylvania has been identified as a lake effect state and Nu-Metrics' Groundhog and Boschung sensors will be tested.

The project team has tested all but Nu-Metrics' Groundhog in the laboratory. Because new technologies may be implemented in the future, the tests have been designed to be able to be run with any sensor. They are also designed to be simple to execute and interpret.

The preliminary testing, with the SRF engineer, is expected to be completed by December 2004. The Minnesota state visit is targeted to be completed January 2005. The Nevada and Pennsylvania visits are targeted to be completed by March 2005. Colorado and Utah have been chosen as backup mountain terrain states if it is not possible to conduct the field testing in Nevada.

2.2. Personnel Training

Training will primarily be done indoors with a PowerPoint presentation or video. The testing equipment will be on hand so that the presenter can illustrate the procedures effectively. After the indoor training, the trainees and presenter will go outside to a nearby parking lot for a dry run of each of the tests.

Because the trainees will need to run the tests without assistance, they will be encouraged to ask questions during the training. To simulate real life situations, during the field testing, the operator will only have the Field Test Plan to consult regarding test procedures. This will simulate the experience that people in other states would have while running the tests. While there might not be a presenter on hand for tests in other states, there should be an automated presentation or video to clearly explain the procedures. From the questions and lessons learned from the tests, the test procedures will evolve into the Application Guidelines.

Additionally, some states will perform temperature measurement with an infrared (IR) thermometer instead of a thermistor. The NCHRP panel would like to further assess whether IR thermometers are accurate enough to replace the thermistors in the Application Guidelines. In the laboratory tests, the IR thermometers were not as accurate as the thermistor. By conducting this additional testing, these tests will evaluate what amount of accuracy is sufficient for field work.

2.3. Personnel Interviews

Personnel interviews will be conducted after the tests to learn more about the operators. By understanding the operator's background, the way each person performs the tests can be compared with that person's background. Later, the tests may be altered or certain types of people may be recommended to run the tests based on the information learned from these interviews. Because these tests require accuracy and are based on scientific concepts, some of the questions ask information related to educational and occupational background. Other questions aim to learn more about the person's experience following detailed directions.

Interview questions have been written to be open-ended and will capture the operator's experience while running the tests. The questions will be given in an interview format and recorded and later transcribed. These questions may be found in Appendix D.

2.4. Lane Closures

Lane closures are required so that the pavement sensors can be accessed directly. Because the procedures involve contact with the surface of the pavement and sensor, adequate space to safely run the procedures is necessary. Information about safe lane closures may be found in the Manual on Uniform Traffic Control Devices (MUTCD) available from the Federal Highway Administration. Because different states have different policies, it is best to check with the locally adopted MUTCD and any other safety considerations.

The test procedures evaluation process requires the lane to be closed for a significant length of time because the state visits require many runs of each test. Lane closures required in the Application Guidelines will be much shorter.

3. RWIS DATA COLLECTION

In most pavement sensor installations, the sensor passes data to a Remote Processing Unit (RPU), usually located in a cabinet near the site of the pavement sensor. This RPU is often then accessed by a computer via a serial or modem connection. In order to access this data locally at any given field site, it will be necessary to either access the RPU's data with a notebook computer, or call up a central server for the information.

Based on the findings of this research project, RPU manufactures will not release for publication detailed information about how to obtain direct access to the RPU. In addition, each manufacturer has different procedures to access their RPUs. Therefore, it is necessary for the individual states to directly obtain the necessary RPU access procedures from the RPU manufacturers. Once the agency has access to the RPU, the procedures for testing the pavement sensor will be the same for all pavement sensors, regardless of the sensor manufacturer. While the project team is not able to obtain or provide all manufacturers' proprietary instructions, the owner of the equipment should be able to obtain the information necessary to access the RPUs from the manufacturer who they have purchased the equipment from.

Different sensors determine surface conditions in different ways. For example, some RPUs require inputs from atmospheric sensors for precipitation and humidity to determine the surface state. Some RWIS sites use many information inputs to determine a single parameter. Therefore, it is necessary to obtain data from all sensors at an RWIS site, including atmospheric sensors.

Because the tests require timely information, it is best if the pavement sensor data can be read at two minute increments. RWIS data is typically not updated or needed this often. Therefore, in order to run these tests effectively, it will be necessary to give commands to the RPU or configure the CPU to give more frequent updates.

3.1. Methods for Obtaining RPU Data

The following presents two methods for obtaining data from the RPU.

3.1.1. Accessing an RPU Directly

Most RPUs can be configured to send serial data to a computer. A terminal program running on the notebook computer can often read this data if the data rates are set appropriately. Usually, this information is given in a delimited format which can be understood without decoding. For example, the data in the third column might be temperature data, while the fourth column might be a surface state in a binary format, such as "0" for "dry" and "1" for "wet."

In order to access the RPU, each state highway agency should contact the RPU manufacturer to determine the best way to access the data. The manufacturer may also have expertise that will make the testing run more efficiently.

Typical RPUs can send data to a computer over a 9-pin serial connection with an RS-232 connector. This can be connected to the computer via the COM port. This scenario is shown in

Figure 1. In some cases, it may be necessary for a manufacturer's representative to be on hand to access the RPU data directly. In other cases, this person may be able to configure the sensor to make it more useful for the sensor testing.

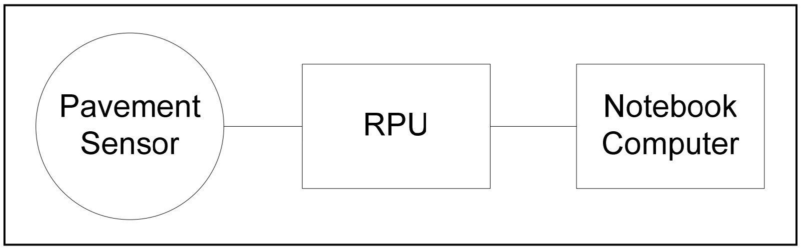


Figure 1. Possible Testing Configuration – Version A

In some cases, the RPU may be connected to a serial server that may be accessed with a TCP/IP connection through a hub at the RWIS site. This type of connection is optimal because the notebook computer may be connected to the RWIS system without changing the way the system functions. This scenario is shown in Figure 2.

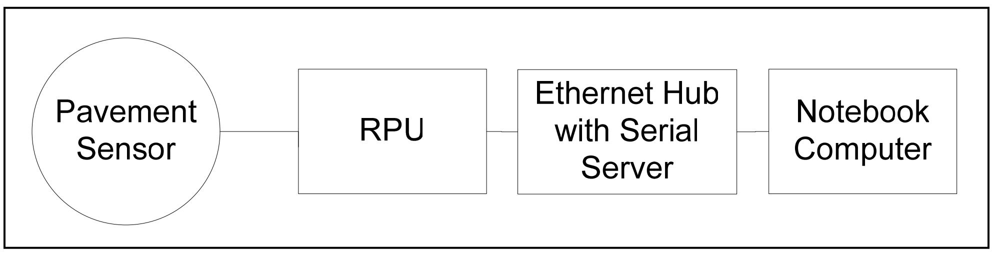


Figure 2. Possible Testing Configuration – Version B

One major consideration for this method is that it requires a method for transferring data from the RPU site to the pavement sensor. This is often 100 feet which may require special hardware to send serial data that distance. Possible solutions are wireless serial data radios or line drivers which send the data over twisted pair. If these solutions are not available, it may be necessary for one operator to stand at the RPU site and tell the other operator the sensor status over a radio. Obviously, this is not an optimal situation, but it removes some of the technical issues.

3.1.2. Call Up Central Server

It will not always be possible to access the RPU by connecting a notebook computer in the field. In those cases, it will be necessary to contact a central office or server to receive the data from the end user. However, these systems may not update frequently enough to get the data required for the Field Test Plan. If this is the case, it may be possible to configure them to update more frequently. This scenario is shown in Figure 3.

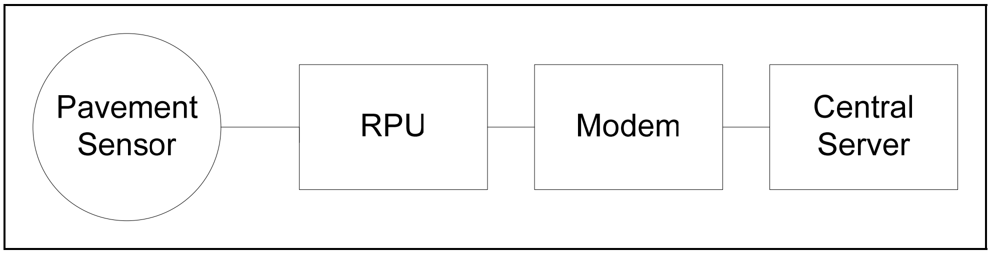


Figure 3. Possible Testing Configuration – Version C

4. FIELD TEST PLAN

The Field Test Plan presents the detailed procedures for testing the performance of in-situ pavement sensors. This section also contains a listing of equipment and supplies for each test.

Field Test Plan Overview

The Field Test Plan has six different tests for testing pavement sensors:

- Field Test 1: Frost Condition
- Field Test 2: Pavement Temperature at Ambient Conditions
- Field Test 3: Pavement Surface Dry/Wet/Ice Conditions
- Field Test 4: Freezing Point of Passive and Active Pavement Sensors
    - Field Test 4A: Testing Freezing Point Using Passive Sensors
    - Field Test 4B: Testing Freezing Point Using Active Sensors
- Field Test 5: Ice Bath at 32º F
- Field Test 6: Pavement Temperature Forced Below Freezing

Equipment Required for All Tests

The following equipment is required for all tests:

- The notebook computer and communication cables are used for accessing the RPU to get the pavement sensor data.
- The knee pad, such as for gardening, is recommended because many of the tests require the operator to work with the pavement sensor directly.
- The paper towels are generally used for cleaning the pavement sensor and are recommended because the thermal paste in Field Test 2 is difficult to wash out of cloth towels.

Notebook computer with communication cables

Knee pad

Paper towels

Additional Equipment to Keep in Testing Toolbox

These items are useful for running the tests, but are not included in the test procedures.

- The refrigerator thermometer will give air temperature, but is not accurate enough to use for testing.
- The paint can opener is for opening the thermal paste can.


Refrigerator Thermometer


Paint Can Opener


Power Inverter


Heater

Field Test 1: Frost Condition

Frost is difficult to create in the field. Rather than creating frost, this test simply observes any frost that is naturally present. Therefore, this test should to be run first, before other tests disrupt the pavement sensor site.

For an RPU to determine frost conditions, it may need atmospheric sensor input. Sometimes, the RPU is programmed such that it uses an algorithm which takes other weather conditions into account, such as air temperature, humidity and precipitation. Because of this dependency on other ESS data, it is especially important that all components of the ESS station are set up properly.

Because naturally occurring frost only occurs during certain times, it may be useful to view the weather conditions from a remote location, such as an RWIS management workstation, to determine the test site's pavement temperature and dew point. Sensor testing can be initiated when the test conditions are satisfied.

Test Conditions

- The pavement surface temperature must be below 32º F.
- The pavement temperature must be less than the dew point temperature.

No Additional Equipment or Supplies Required

Testing Procedures - Field Test 1: Frost Condition

To test the pavement sensor for frost state compliance, perform the following steps:

Step 1 Read all the manuals and manufacturers' literature on operating the participating sensor.

Step 2 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the notebook computer.

Step 3 **Record** the following information from the ESS station on the Testing and Maintenance Forms:

- Record air temperature
- Record pavement temperature
- Record dew point temperature

Step 4 If the pavement temperature is below 32º F and the dew point temperature is less than the pavement temperature, proceed to the next step. If these conditions are not met, frost formation is not possible; Proceed to the next test.

Step 5 Visually observe and the sensor's surface condition. Also observe the RPU surface state sensor reading.

Record the following on the Testing and Maintenance Forms:

- Record visual surface state observation
- Record RPU surface state reading

Field Test 2: Pavement Temperature at Ambient Conditions

Field Test 2 measures the pavement sensor's temperature accuracy.

Test Conditions

- This test may be done at any temperature where reasonable test conditions can be maintained. The test should be done around daybreak to avoid solar radiation. The sensor and thermistors must be shaded from solar radiation for 15 minutes prior to the test and during the test.
- If the test must be done after the pavement sensor has been warmed by the sun, the sensor must be shielded for an hour or more.
- The sensor surface should remain dry and clean throughout the test.
- The thermal paste becomes stiff if subjected to cold temperatures. It is best to keep the thermal paste warm until it is needed.
- The thermistor will require time to stabilize after being handled.

Equipment and Supplies Required

		
Thermal conducting paste (Omegatherm© OB-201)	Paint can opener	Two handheld thermometers (Omega HH41) with precision thermistors (Omega ON-409-PP)
		
Watch for keeping time	Shelter tent such as collapsible ice fishing shelter	Brick with insulation on bottom surface to secure thermistor lead wires
		
Supply of tap water to clean pavement		

Testing Procedures - Field Test 2: Pavement Temperature at Ambient Conditions

To test the pavement sensor for temperature compliance, perform the following steps:

Step 1 Read all the manuals and manufacturers' literature on operating the participating sensor.

Step 2 Shield the pavement sensor from solar radiation to block the effects of the environment. Wait at least 15 minutes for the effects of the solar radiation to dissipate before taking the first reading.

Step 3 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the notebook computer.

Step 4 Clean and dry the sensor and surrounding one foot area using paper towels.

Step 5 Affix one thermistor to the sensor and one thermistor to the pavement 2.5" from the edge of the sensor using thermally conductive paste as shown in Figure 2-1. The metallic side of the thermistor should face down. Place the insulated brick on the thermistors. Attach the lead wires from the thermistors to the thermometers.

Step 6 **Record** the following readings at two minute intervals on the Testing and Maintenance Form until the stability has been met for both the thermistors and the pavement sensor:

- Pavement sensor temperature (from RPU)
- Thermistor on pavement sensor
- Thermistor 2.5" from edge of sensor
- Infrared gun on sensor (as close to thermistor as possible)
- Infrared gun 2.5" from edge of sensor (as close to thermistor as possible)

Stability occurs when the both thermistor and pavement sensor vary less than 0.4º F (0.2º C) between four successive readings.

Step 7 Clean thermal paste from the surface of the pavement sensor with the paper towels and brass brush. First wipe as much thermal paste with the paper towels. Clean any residual thermal paste off the sensor with the brass brush.

Figure 2-1. Applying Thermal Paste to Sensor

Field Test 3: Pavement Surface Dry/Wet/Ice Conditions

Field Test 3 includes tests for determining dry, wet and ice surface state conditions. Most RPUs determine whether the sensor is dry or not dry by measuring the conductivity of two electrodes on the sensor. Depending on the sensor, the RPU may also use temperature information to detect ice.

Test Conditions

- The weather must be dry or the sensor must be sheltered from precipitation.
- To form ice, the pavement temperature must be below 32º F. The thermistor and thermometer may be used to check the air temperature.
- Dry and wet surface state compliance can be evaluated at all temperatures. Before freezing, the sensor should give a "wet" reading.
- If required by the RPU, atmospheric sensors must be connected and working properly.

Equipment and Supplies Required

The following equipment and supplies are needed for testing dry/wet/ice conditions.

Heat gun

Modified misting bottle filled with tap water

Watch for keeping time

0.5mm feeler gauge to measure film depth

Thermometer and thermistor to check air temperature

Testing Procedures - Field Test 3: Pavement Surface Dry/Wet/Ice Conditions

To test the pavement sensor for dry, wet and ice state compliance, perform the following steps:

Step 1 Read all the manuals and manufacturers' literature on operating the participating sensor.

Step 2 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the notebook computer.

Step 3 Use water and paper towels to clean the pins on the top of the pavement sensor. Dry the subject sensor with the dry towels and heat gun.

Step 4 **Record** the following on the Testing and Maintenance Forms every two minutes until a dry pavement surface state reading is recorded:

- Visual surface state observation of the pavement sensor
- Pavement surface state (from RPU)

Step 5 Shake the misting bottle and uniformly spray a 0.5mm tap water film on the surface of the sensor. Check the film thickness with the feeler gauge. If the film does not stay on the sensor, place a paper towel on the sensor and continue to perform the procedure.

Record the following on the Testing and Maintenance Form at two minute intervals until the RPU reports the wet surface state or ten minutes have expired:

- Time of day
- Visual surface state observation of the pavement sensor (dry/wet/ice)
- Pavement surface state (from RPU)

Step 6 If the pavement temperature is below 32º F, continue to record data until the RPU reports an ice condition. Conclude the test if RPU surface state does not update in a reasonable amount of time.

Figure 3-1. Cleaning Pavement Sensor Depression with Paper Towel.

Figure 3-2. Spraying Tap Water on Sensor Surface.

Field Test 4: Freezing Point of Passive and Active Pavement Sensors

Depending on whether the ESS station has a sensor that finds freezing point with an active or passive sensor, either Field Test 4A or Field Test 4B should be run.

Field Test 4A: Freezing Point of Passive Sensors

For passive sensors to measure the freezing point of a particular brine on the sensor surface, the sensor manufacturer has to program the CPU for that brine. The sensor generally determines the freezing point temperature by measuring the conductivity of the brine between the electrodes on the sensor surface. The relative conductivity values of five brines are shown in Appendix A.

A number of different passive pavement sensors are not capable of determining the freezing point temperatures of high concentrations of brine. For the state visits, the procedures given in Test 4A should be run at 4%, 10%, 15% and 23% concentrations, or until the sensor fails. This is meant to develop a fuller understanding of the accuracy of passive pavement sensors.

Field Test 4B: Freezing Point of Active Sensors

An active pavement sensor can be used to determine the freezing point temperature of any brine or mixtures of brine. A Peltier device warms then cools the solution on the sensor. As the device cools the solution on the surface of the sensor, the temperature stabilizes as the liquid changes phase to solid. The RPU detects that the sensor has reached its freezing point and returns that temperature as the freezing point. This process is generally more accurate and is more robust because the freezing point is measured directly, not through conductivity values that are dependent on chemical type. However, the test takes longer to run because of the heating and cooling cycles.

Field Test 4A: Testing Freezing Point Using Passive Sensors

This test procedure will measure how well a passive sensor can detect a chemical concentration's freezing point. The chemical solution should correspond with the solution that the RPU is set up to measure. The RPU is should be configured for the type of brine used in maintenance operations.

The procedures to prepare the various chemical concentrations can be found in Appendix B.

Test Conditions

- Ambient pavement temperature must be below 32º F and above the brine's freezing point See Appendix B for brine properties.
- Passive sensors are very sensitive to concentration changes and film thickness. It is important to thoroughly clean the pavement sensor between runs with distilled water.

Equipment and Supplies Required

		
Watch for keeping time	Shelter tent such as an ice fishing shelter	One gallon of distilled water
		
0.5mm feeler gauge to measure film depth	Modified misting bottles filled with 4%, 10%, 15% and 23% salt solutions	Heat gun

Testing Procedures - Field Test 4A: Freezing Point Using Passive Sensors

To test passive pavement sensors for freezing point accuracy, perform the following steps:

Step 1 Read all the manuals and manufacturers' literature on operating the participating sensor. Determine from which chemical the sensor is programmed to monitor.

Record the chemical on Testing and Maintenance Form.

Step 2 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the notebook computer.

Step 3 Repeatedly flush the top of the sensor with distilled water and clean the pins on the top of the pavement sensor with paper towels. Clean and dry the subject sensor and surrounding area using paper towels. If necessary, dry the sensor with the heat gun.

Step 4 Shake the bottle with the lowest concentration salt solution and spray a 0.5mm film on the entire surface of the sensor. If the sensor has a well or depression, fill it with the solution. If the film does not stay on the sensor, place a paper towel on the sensor and continue to perform the procedure.

Record the type of salt solution on the Testing and Maintenance Form.

Record the following on the Testing and Maintenance Form at two minute intervals until the stability criteria is met:

- Time of day
- Freezing point (from RPU)

Stability criteria is met when the pavement sensor freezing point has varied less than 3.6º F (2.0º C) between four successive readings.

Step 5 Repeat steps 3-5 for the next most concentrated solution until the sensor fails.

The sensor fails when it gives overestimates of the salt solution concentration by more than 5.0º F (2.8º C).

Field Test 4B: Testing Freezing Point Using Active Sensors

This test will measure the freezing point performance of active pavement sensors by exposing the sensor to ten percent concentrations of salt solution. The procedures to prepare the various chemical concentrations can be found in Attachment B. In contrast to Field Test 4A, the salt solution type is not relevant to the outcome of this test because active sensors detect freezing point without any user input about salt solution type.

Test Conditions

- Ambient pavement temperature must be near the freezing point of the chemical. 10% sodium chloride freezes at 20.2º F. 10% magnesium chloride freezes at 17.9º F.
- It is important to thoroughly clean the pavement sensor with distilled water.

Chemical Type	Freezing Point at 10% Concentration
Sodium Chloride	20.2º F
Magnesium Chloride	17.9º F
Calcium Chloride	21.5º F

Equipment and Supplies Required

		
Watch for keeping time	Shelter tent such as ice fishing shelter	Modified misting bottle filled with 10% percent of salt solution
		
Brass brush to clean the pins on top of the sensor	0.5mm feeler gauge to measure film depth	One gallon of tap water

Testing Procedures - Field Test 4B: Freezing Point Using Active Sensors

To test the pavement sensor for measuring freezing point temperatures, perform the following steps:

Step 1 Read all the manuals and manufacturers' literature on operating the participating sensor.

Step 2 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the notebook computer.

Step 3 Read the temperature output values from the pavement sensor. If it is reasonably close to the chemical's freezing point, proceed to Steps 4 to 6 (see Appendix B).

If the temperature is too warm, the active sensor will not be able to freeze the solution. If it is too cold, the heating element will not thaw the chemical solution.

Step 4 Repeatedly flush the top of the sensor with distilled water and clean the pins on the top of the pavement sensor with paper towels. Clean and dry the subject sensor and surrounding area using paper towels.

Step 5 Shake the misting bottle with and spray a 0.5mm film on the sensor. If the film does not stay on the sensor, place a paper towel on the sensor and continue to perform the procedure.

Record the type of salt solution on the Testing and Maintenance Form.

Step 6 **Record** sensor readings every cycle for a minimum of three cycles on the Testing and Maintenance Form.

Field Test 5: Ice Bath at 32º F

Test Conditions

- It is necessary to create the required condition by using an ice water bath.
- This test may only be run on sensors with temperature sensing elements located near the surface of the sensor. If the temperature sensing element is too far below the surface, the test may take too long to conduct because of the time required to cool the sensor to a sufficient depth.
- The ambient temperature of the pavement must be between 32º F and 50º F.
- Ice may be crushed before going out to the ESS site or at the site. To crush the ice on-site, put the ice in a canvas bag such as a bituminous sample bag and crush the ice with the brick used in Field Test 2.

Equipment and Supplies Required

		
Thermal conducting paste (Omegatherm© OB-201)	One handheld thermometer (Omega HH41) with precision thermistors (Omega ON-409-PP)	Shelter tent such as ice fishing shelter
		
Stirring instrument such as a plastic slotted spoon	10-inch section of 12-inch diameter PVC pipe	One gallon of chilled (below 40º F) distilled water
		
Watch for keeping time	10 pounds of crushed ice cubes	Plastic bag

Testing Procedures - Field Test 5: Ice Bath at 32º F

To test the pavement sensor for temperature compliance, perform the following steps:

Step 1 Read all the manuals and manufacturers' literature on operating the participating sensor.

Step 2 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the notebook computer.

Step 3 Clean and dry the subject sensor and surrounding area using paper towels.

Step 4 Place the PVC section around the pavement sensor. Slide the thermistor under the edge of the PVC so that the thermistor rests on the pavement sensor

Step 5 Put the large plastic bag in the PVC with the bag overlapping the edges of the PVC as shown in Figure 5-1. Fill the pipe section with the gallon of distilled water.

Step 6 Add enough crushed ice to produce a thick layer of slushy ice in the bath.

Step 7 Stir the mixture continuously.

Record the following on the Testing and Maintenance Form at two minute intervals until 20 minutes have expired:

- Time of Day
- Pavement Temperature (From RPU)
- Thermistor temperature

Figure 5-1. Bag Placed Over PVC section.

Figure 5-2. Distilled Water Poured in PVC and Bag.

Figure 5-3. Ice Poured Into PVC and Plastic Bag.

Field Test 6: Pavement Temperature Forced Below Freezing

This test demonstrates that the subject sensor can monitor surface temperatures that are very cold. Even if the sensor is working properly, it may reveal temperature limitations of the sensor. It is necessary to create the temperature condition by applying dry ice to the surface of the pavement sensor.

Test Conditions

- If an ice shelter or other confining space is used to shade the pavement sensor, remove it from the pavement sensor. Sublimated CO_2 displaces oxygen and could create a safety hazard if the gases are confined.
- The ambient temperature of the pavement must be below 50º F and ideally below 32º F.
- Run this test last. The pavement will become too cold to conduct additional tests accurately.
- No thermistors are required for this test.

Equipment and Supplies Required

		
Styrofoam container to keep dry ice cold	10” x 10” block of dry ice	Insulated gloves

Testing Procedures - Field Test 6: Pavement Temperature Forced Below Freezing

To test the pavement sensor for temperature compliance, perform the following steps:

Step 1 Read all the manuals and manufacturers' literature on operating the participating sensor.

Step 2 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the notebook computer.

Step 3 Clean and dry the subject sensor using a paper towels.

Step 4 Place dry ice on the pavement sensor for duration of 20 minutes.

Record pavement sensor temperature and surface state readings from the RPU at two minute intervals on the Testing and Maintenance Form.

After 20 minutes have expired, remove the dry ice and continue to take sensor readings for an additional 10 minutes.

Figure 6-1. Placing Dry Ice on Pavement Sensor.

Figure 6-2. Dry Ice Resting on Pavement Sensor.

APPENDIX A
Phase Diagrams and Conductivity Curves for Brines

Because different chemicals have different properties, it may be beneficial to know about the properties of salt solutions to configure the RPU.

Solution Phase Diagrams

For the evaluators of pavement sensors to have some idea of the behavior of the various brines in regards to their concentrations and temperatures, Figure A-1 is provided for reference. As can be seen, each brine has its own characteristics.

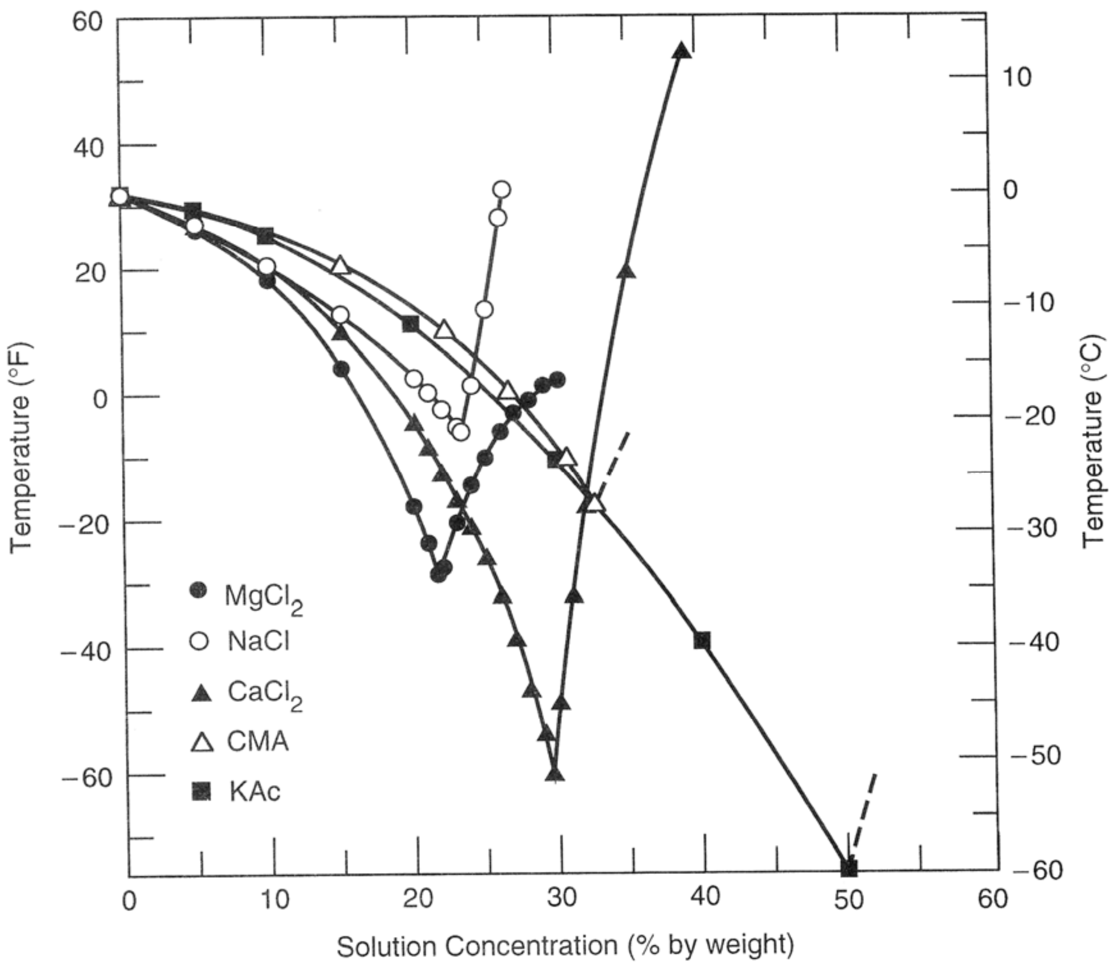


Figure A-1. Phase Diagrams of Five Brines

Conductivity Curves and Values for Solutions

During the research work for the Strategic Highway Research Program's (SHRP) project: "Development of Anti-Icing Technology" [3], laboratory studies were conducted to evaluate the utility of the SOBO-20 salinity tester for the semi-quantitative measurement of chemical solutions applied to pavement surfaces. The studies consisted of evaluating the type of response and range of detection for five different chemicals.

The results of the laboratory studies that included the conductivity measurements for the five chemical brines are presented in tables G-5, G-6, and G-7. In addition, a composite presentation of the test data is set forth in Figure G-2.

This information is provided so that the evaluator can have a sense of the magnitude of the conductivity values for sodium chloride, magnesium chloride, and calcium solutions.

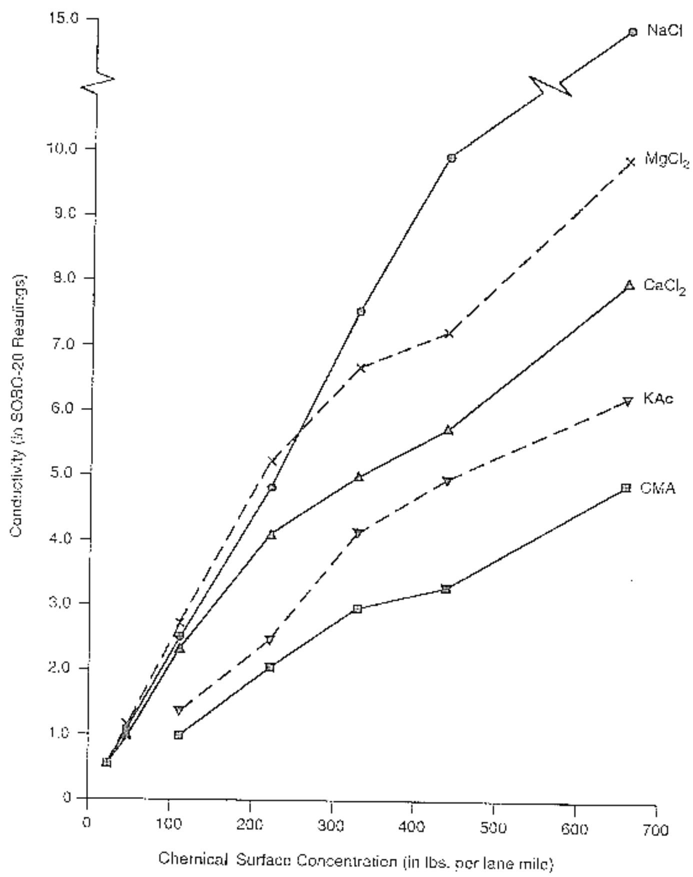


Figure A-2. SOBO-20 Readings versus Chemical Surface Concentration for Five Brines
**Source: SHRP-H-385, Development of Anti-Icing Technology, Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.*

Table A-1. SOBO-20 Readings and Conductivity Values of Sodium Chloride Solutions

SOBO meter		Actual Reading [a]	Applied chemical surface concentration			Conductivity [a] (µS)
Observed Reading [a]	Scale Factor		(oz/yd^2)	(g/m^2)	(lb/lane mile)	
1	x ½	0.5	0.05	1.7	22	180
1	x 1	1	0.1	3.39	44	308
5	x 1/2	2.5	0.25	8.48	110	767
4.8	x 1	4.8	0.5	17	220	1,517
10	x 1/2	5	0.5	17	220	1,567
15	x 1/2	7.5	0.75	25.4	330	2,500
10	x 1	10	1	33.9	440	3,250
15	x 1	15	1.5	50.9	660	4,767

[a]Average of three determinations

Table A-2. Readings and Conductivity Values of Magnesium Chloride Solutions

SOBO meter		Actual Reading [a]	Applied chemical surface concentration			Conductivity [a] (µS)
Observed Reading [a]	Scale Factor		(oz/yd^2)	(g/m^2)	(lb/lane mile)	
1.00	x ½	0.50	0.05	1.7	22	135
1.00	x 1	1.00	0.10	3.39	44	250
2.75	x 1/2	1.38	0.25	8.48	110	602
5.25	x 1	5.25	0.50	17	220	1,185
10.00	x 1/2	5.00	0.50	17	220	1,222
13.38	x 1/2	6.69	0.75	25.4	330	2,712
7.25	x 1	7.25	1.0	33.9	440	3,500
10.00	x 1	10.00	1.50	50.9	660	5,075

[a]Average of three determinations

Table A-3. Readings and Conductivity Values of Calcium Chloride Solutions

SOBO meter		Actual Reading [a]	Applied chemical surface concentration			Conductivity [a] (µS)
Observed Reading [a]	Scale Factor		(oz/yd^2)	(g/m^2)	(lb/lane mile)	
1.00	x ½	0.50	0.05	1.7	22	135
1.00	x 1	1.00	0.10	3.39	44	250
4.90	x 1/2	2.45	0.25	8.48	110	602
3.90	x 1	3.90	0.50	17	220	1,185
8.80	x 1/2	4.40	0.50	17	220	1,222
10.00	x 1/2	5.00	0.75	25.4	330	2,712
5.75	x 1	5.75	1.0	33.9	440	3,500
8.00	x 1	8.00	1.50	50.9	660	5,075

[a]Average of three determinations

APPENDIX B
Procedures For Preparing Chemical Concentrations

In order to run the freezing point tests in Field Test Plan 4, it is necessary to prepare chemical solutions before going out to an ESS station.

This appendix contains procedures and tables of physical properties of the following chemical concentrations:

Sodium Chloride Brine Preparation

The following equipment and supplies are necessary to prepare the given concentrations of chemical brine to be used for testing the Freezing Point parameter of a pavement sensor.

- Supply of deiodized dry salt, such as table salt. Do not obtain salt from maintenance stockpiles as that salt has approximately 5% impure materials besides the salt.
- Supply of deionized or distilled water
- A scale that will weigh to the nearest gram or 0.03 oz.
- Supply of one-quart jars with lids.
- Testing cylinder with hydrometer

The following procedures are to be used in preparing the various concentrations of salt brine:

Step 1 Fill a clean one-quart jar approximately 2/3 full of deionized or distilled water.

Step 2 From Table B-1, determine the amount of salt required to make one quart of solution at the desired concentration level.

Step 3 Weigh out the necessary amount of salt and gradually pour it into the jar while stirring the solution. Continue to stir until the salt is dissolved.

Step 4 Add deionized or distilled water to the jar to bring the level to the top of the jar. Screw the cap on the jar. Shake the jar to mix the solution.

Step 5 Remove the lid and pour some solution into a cylinder. Test the specific gravity of the solution with a hydrometer. Compare the readings with those in Table B-1.

Step 6 Replace the lid and label the jar with the chemical type and concentration.

Table B-1. Proportions for Preparing Sodium Chloride Solutions

% NaCl Concentration	Weight NaCl per quart of solution Oz (Grams)	Freezing Point Temperature ºC (º F)	Specific Gravity at 20.0º C (68.0º F)
1	0.34 (9.6)	-0.59 (30.93)	1.007
4	1.37 (38.9)	-2.4 (27.7)	1.0286
10	3.58 (101.4)	-6.6 (20.2)	1.0726
15	5.55 (157.4)	-10.9 (12.4)	1.1105
23	9.00 (255.1)	-20.7 (-5.2)	1.1721

The following table may be used as a reference when preparing the sodium chloride solutions.

Table B-2. Physical Properties of Sodium Chloride

% NaCl by weight	Specific Gravity at 20.0º C (68.0º F)	Amount of NaCl per quart of solution oz (grams)	Freezing Point (ºF)	Freezing Point (ºC)
1.00	1.0071	0.34 (9.56)	30.933	-0.593
2.00	1.0143	0.67 (19.12)	29.865	-1.186
3.00	1.0214	1.02 (28.96)	28.778	-1.790
4.00	1.0286	1.37 (38.90)	27.664	-2.409
5.00	1.0358	1.73 (48.93)	26.517	-3.046
6.00	1.0431	2.09 (59.15)	25.335	-3.703
7.00	1.0504	2.45 (69.46)	24.120	-4.378
8.00	1.0578	2.82 (79.97)	22.858	-5.079
9.00	1.0651	3.19 (90.57)	21.547	-5.807
10.00	1.0726	3.58 (101.35)	20.185	-6.564
11.00	1.0801	3.96 (112.24)	18.765	-7.353
12.00	1.0876	4.35 (123.31)	17.283	-8.176
13.00	1.0952	4.74 (134.48)	15.732	-9.038
14.00	1.1028	5.14 (145.83)	14.108	-9.940
15.00	1.1105	5.55 (157.38)	12.402	-10.888
16.00	1.1182	5.96 (169.02)	10.607	-11.885
17.00	1.1260	6.38 (180.85)	8.717	-12.935
18.00	1.1339	6.80 (192.77)	6.721	-14.044
19.00	1.1418	7.23 (204.98)	4.611	-15.216
20.00	1.1498	7.66 (217.28)	2.376	-16.458
21.00	1.1579	8.10 (229.68)	0.003	-17.776
22.00	1.1660	8.55 (242.36)	-2.517	-19.176
23.00	1.1721	9.00 (255.14)	-5.201	-20.667

Source: CRC handbook of Chemistry and Physics, 52nd edition, CRC Press, Boca Raton FL 1972, p. D-213 & D-214.

Magnesium Chloride Brine Preparation

Magnesium Chloride is usually used by highway agencies in liquid form. It is normally marketed in a 30% concentration. However, it can be purchased in solid (flake) form. In preparing solutions of magnesium chloride brine to be used for testing the freezing point parameter of a pavement sensor, it is recommended that liquid material be obtained and a hydrometer reading be taken of the material at 60º F. The material may then be diluted down to the desired concentration.

The following equipment and supplies are necessary to prepare the given concentrations of chemical brine to be used for testing the Freezing Point parameter of a pavement sensor.

- Supply of liquid magnesium chloride brine
- Supply of deionized or distilled water
- Supply of one-quart jars with lids.
- A two-quart glass container
- A graduated cylinder with hydrometer

The following procedures are to be used in preparing the various concentrations of magnesium chloride brine:

Step 1 Take a temperature reading of the supply of available magnesium chloride brine. If the temperature is not 68º F, either raise or lower the temperature to 60º F.

Step 2 Take a hydrometer reading of the magnesium chloride brine and record the data. If the solution has a concentration of 30%, the specific gravity reading should be 1.283. If not, use the hydrometer reading obtained in the calculations outlined below.

Step 3 From Table B-3, determine the specific gravity of the desired concentration.

Step 4 Perform the calculation as shown in Figure B-1 to determine the amount of dilution required.

Step 5 Pour 50 mL of the strong magnesium chloride brine in the two-quarter container.

Step 6 Pour the calculated amount of deionized or distilled water from graduated cylinder into the two-quart container and mix the solution.

Step 7 Pour the diluted solution in a one quart jar and place the lid on the jar. Label the jar with the chemical type and concentration.

Step 8 The concentration of the diluted brine can be checked with a hydrometer reading if it is near 60º F.

Table B-3. Properties for Preparing Magnesium Chloride Brine

% $MgCl_2$ Concentration	**Crystallization Temperature (ºF)**	**Specific Gravity at 15.6º C (60.0º F)**
4	27.8	1.010
10	17.9	1.086
15	4.0	1.132
21.6	-28	1.196
30	3.0	1.283

The following formula may be used to determine the amount of deionized or distilled water needed to dilute a strong solution at 60º F.

- "% Strong" is the original concentration
- "% Weak" is the targeted concentration

$$\left[\frac{\%\ \text{Strong} - \%\text{Weak}}{\%\ \text{Weak}}\right] \text{X} \quad \text{Specific gravity of Strong Solution}$$

Figure B-1. Dilution Formula for Magnesium Chloride

Example: Assuming the strong brine has a concentration of 30%, its specific gravity is 1.283, and volume of 50 mL. Concentration of 10% is required of the dilution solution.

$$\left(\frac{30 - 10}{10}\right) * 1.283 = 2.566$$

2.566 X 50 mL = 128.3 mL

Add 128 mL of deionized or distilled water to the 50 mL of the 30% concentration of magnesium chloride brine to create a 10% concentration of magnesium chloride brine.

Figure B-2. Example of Magnesium Chloride Dilution

Table B-3 provides the properties of the various concentrations of magnesium chloride brine. If different concentrations are needed than those shown in Table B-3, the appropriate values can be obtained from Table B-5, Properties of Magnesium Chloride Brine. The above formula can be used to determine the amount of dilution required. Table B-6 provides the dilution factors and the amount of deionized or distilled water that must be added to either 30% or 21.6% concentrations of magnesium chloride brine. These two values are generally the concentrations that are marketed by vendors to highway agencies.

Table B-4. Dilution Factors and Amount of Water to be Added to Obtain Desired Solutions

Desired % $MgCl_2$ Concentration	30 % Concentration		21.6 % Concentration	
	Dilution Factors	mL of water to be added*	Dilution Factors	mL of water to be added*
4	8.340	417	5.262	263
10	2.566	128	1.387	69
15	1.283	64	0.526	26
21.6	0.499	25	-	0
30.0	-	0	N/A	N/A

*Amount of deionized or distilled water to be added to 50 mL of concentration of magnesium chloride brine required to create the desired concentration of magnesium chloride brine.

Table B-5. Properties of Magnesium Chloride Brine

% by Weight	Specific Gravity at 15.6° C (60.0° F)	Freezing Point Celsius	Freezing Point Fahrenheit
5	1.013	-2.11	26.4
6	1.051	-3.09	25.0
7	1.060	-4.72	23.5
8	1.069	-5.67	21.8
9	1.070	-6.67	20.0
10	1.086	-7.83	17.9
11	1.096	-9.05	15.7
12	1.105	-10.50	13.1
13	1.114	-12.10	10.3
14	1.123	-13.70	7.3
15	1.132	-15.90	4.0
16	1.142	-17.60	0.4
17	1.151	-19.70	-3.5
18	1.161	-22.10	-7.7
19	1.170	-25.60	-12.2
20	1.180	-27.40	-17.2
21	1.190	-30.50	-23.0
22	1.200	-32.80	-27.0
23	1.210	-28.90	-20.0
24	1.220	-25.60	-14.0
25	1.230	-23.30	-10.0
26	1.241	-21.10	-6.0
27	1.251	-19.40	-3.0
28	1.262	-18.30	-1.0
29	1.273	-17.20	1.0
30	1.283	-16.70	3.0

Source: Chemical Deicer Specifications for the Pacific Northwest States of Idaho, Montana, Oregon, Washington State, p 25.

Calcium Chloride Brine Preparation

Calcium Chloride is usually used by highway agencies in liquid form. It is normally marketed in a 30% concentration. However, it can be purchased in solid (flake) form. In preparing solutions of calcium chloride brine to be used for testing the Freezing Point parameter of a pavement sensor, it is recommended that liquid material be obtained, and a hydrometer reading be taken of the material at 68º F (20° C). The material than be diluted down to the desired concentration.

The following equipment and supplies are necessary to prepare the given concentrations of chemical brine to be used for testing the Freezing Point parameter of a pavement sensor.

- Supply of liquid calcium chloride brine
- Supply of deionized or distilled water
- Supply of one-quart jars with lids.
- A two-quart glass container
- A graduated cylinder with hydrometer

The following procedures are to be used in preparing the various concentrations of calcium chloride brine:

Step 1 Take a temperature reading of the supply of available calcium chloride brine. If the temperature is not 68º F, either raise or lower the temperature to 68º F.

Step 2 Take a hydrometer reading of the calcium chloride brine and recorded the data. If the solution has a concentration of 30%, the specific gravity reading should be 1.2816. If not, use the hydrometer reading obtained, in the calculations outlined below.

Step 3 From Table B-3, determine the specific gravity of the desired concentration.

Step 4 Perform the calculation as shown in Figure B-1 to determine the amount of dilution required.

Step 5 Pour 50 mL of the strong magnesium chloride brine in the two-quarter container.

Step 6 Pour the calculated amount of deionized or distilled water from graduated cylinder into the two-quart container and mix the solution.

Step 7 Pour the diluted solution in a one quart jar and place the lid on the jar. Label the jar with the chemical type and concentration.

Step 8 The concentration of the diluted brine can be checked with a hydrometer reading if it is near 68º F.

Table B-6. Properties for Preparing Calcium Chloride Brine

% $CaCl_2$ Concentration	**Crystallization Temperature in ºC (ºF)**	**Specific Gravity at 20.0º C (68.0º F)**
1	31.21 (-0.44)	1.0065
4	28.73 (-1.82)	1.0316
10	21.45 (-5.86)	1.0835
15	12.18 (-11.01)	1.1292
30	-41.80 (-41.00)	1.2816

Source: CRC Handbook of Chemistry and Physics, 52th edition, CRC Press, Boca Raton, FL 1972, p. D 224

The following formula may be used to determine the amount of deionized or distilled water needed to dilute a strong solution at 68º F.

- "% Strong" is the original concentration
- "% Weak" is the targeted concentration

$$\left[\frac{\text{\% Strong - \%Weak}}{\text{\% Weak}}\right] \text{X} \quad \text{Specific gravity of Strong Solution}$$

Figure B-3. Dilution Formula for Calcium Chloride

Example: Assuming the strong brine has a concentration of 30%, its specific gravity is 1.283, and volume of 50 mL. Concentration of 10% is required of the dilution solution.

$$\left(\frac{30 - 10}{10}\right) * 1.2816 = 2.5632$$

2.566 X 50 mL = 128.3 mL

Add 128 mL of deionized or distilled water to the 50 mL of the 30% concentration of calcium chloride brine to create a 10% concentration of calcium chloride brine.

Figure B-4. Example of Calcium Chloride Dilution

Table B-6 provides the properties of the various concentrations of calcium chloride brine. If different concentrations are needed than those shown in Table B-6, the appropriate values can be obtained from Table B-8, Properties of Calcium Chloride Brine. The above formula can be used to determine the amount of dilution required. Table B-7 provides the dilution factors and the amount of deionized or distilled water that must be added to either 30% or 21.6% concentrations of calcium chloride brine. These two values are generally the concentrations that are marketed by vendors to highway agencies.

Table B-7. Dilution Factors and Amount of Water to be Added to Obtain Desired Solutions

Desired % $CaCl_2$ Concentration	**30 % Concentration**		**21.6 % Concentration**	
	Dilution Factors	**mL of water to be added***	**Dilution Factors**	**mL of water to be added***
1	37.166	1858	1	37.166
4	8.3304	417	4	8.3304
10	2.563	128	10	2.563
15	1.2816	64	15	1.2816
30.0	-	0	30.0	-

*Amount of deionized or distilled water to be added to 50 mL of concentration of magnesium chloride brine required to create the desired concentration of magnesium chloride brine.

Table B-8. Properties of Calcium Chloride Brine

% by Weight	Specific Gravity at 68° F (20° C)	Freezing Point Celsius	Freezing Point Fahrenheit
1	1.0065	-0.44	31.21
2	1.0148	-0.88	30.42
3	1.0232	-1.33	29.61
4	1.0316	-1.82	28.73
5	1.0401	-2.35	27.78
6	1.0486	-2.93	26.73
7	1.0572	-3.57	25.57
8	1.0659	-4.28	24.31
9	1.0747	-5.04	22.93
10	1.0835	-5.86	21.45
11	1.0923	-6.74	19.87
12	1.1014	-7.70	18.14
13	1.1105	-8.72	16.30
14	1.1198	-9.83	14.31
15	1.1292	-11.01	12.18
16	1.1386	-12.28	9.90
17	1.1482	-13.65	7.43
18	1.1579	-15.11	4.80
19	1.1677	-16.70	1.94
20	1.1775	-18.30	-0.94
21	1.1876	-20.00	-4.00
22	1.1976	-21.70	-7.06
23	1.2078	-23.50	-10.30
24	1.2180	-25.30	-13.54
25	1.2284	-27.50	-17.50
26	1.2388	-29.70	-21.46
27	1.2494	-32.20	-25.96
28	1.2600	-34.70	-30.46
29	1.2708	-37.85	-36.13
30	1.2816	-41.00	-41.80

Source: Chemical Deicer Specifications for the Pacific Northwest States of Idaho, Montana, Oregon, Washington State, p 25.

APPENDIX C
Testing and Maintenance Forms for Pavement Sensors

Name: ____

Organization: ____

Date: ____

Location of ESS:____

Location of Pavement Sensor (if multiple sensors): _________________________________

Sensor Serial Number: ______________________Sensor Manufacturer: _________________

Temperature______________________________ Weather Conditions___________________

Physical Observation of Pavement Sensor on Arrival

Action Recommendation (to be completed after testing)

APPENDIX D
Interview Questions

The following questions will be asked after the testing has been completed to understand how different people react to the test procedures. For example, an operator may have difficulty performing a certain procedure depending on that person's previous RWIS experience While the test procedures have been shown to be theoretically scientifically sound in the laboratory, tests in the field may reveal new parameters which need to be accounted. This survey will be conducted in interview form.

The following questions will be asked of each of the operators during the interview:

Contact Information

- Name
- Agency
- Phone
- E-mail

Determine RWIS/Testing Experience

- What type of RWIS experience do you have? How often?
    - Do you maintain RWIS systems?
- Have you had prior testing experience?
    - Work experience in a laboratory environment?
    - Work experience in construction (such as proctor, slump test, gradation)?
    - Other environments that required following step-by-step instructions
        - Do you work well by following step-by-step instructions?
- Do you use RWIS data in your job?
    - When or where do you see RWIS data?
    - How do you use RWIS?
        - On truck?
        - Forecasting?
        - Quality control?
        - Other?

Reaction to Test Procedures

- How confident are you that the thermistor baseline was accurate?
    - What was your experience with the thermistor baseline?
- How confident are you that the infrared gun baseline was accurate?
    - What was your experience with the infrared gun baseline?
- Was the time required for each test appropriate?
    - Field Test 1: Frost Condition
    - Field Test 2: Pavement Temperature at Ambient Conditions
    - Field Test 3: Pavement Surface Dry/Wet/Ice Conditions
    - Field Test 4: Freezing Point of Passive and Active Pavement Sensors
        - Field Test 4A: Testing Freezing Point Using Passive Sensors
        - Field Test 4B: Testing Freezing Point Using Active Sensors
    - Field Test 5: Ice Bath at 32º F
    - Field Test 6: Pavement Temperature Forced Below Freezing
- Were any steps unnecessary?
    - Field Test 1: Frost Condition
    - Field Test 2: Pavement Temperature at Ambient Conditions
    - Field Test 3: Pavement Surface Dry/Wet/Ice Conditions
    - Field Test 4: Freezing Point of Passive and Active Pavement Sensors
        - Field Test 4A: Testing Freezing Point Using Passive Sensors
        - Field Test 4B: Testing Freezing Point Using Active Sensors
    - Field Test 5: Ice Bath at 32º F
    - Field Test 6: Pavement Temperature Forced Below Freezing
- Did you deviate from any test procedures?
    - Field Test 1: Frost Condition
    - Field Test 2: Pavement Temperature at Ambient Conditions
    - Field Test 3: Pavement Surface Dry/Wet/Ice Conditions
    - Field Test 4: Freezing Point of Passive and Active Pavement Sensors
        - Field Test 4A: Testing Freezing Point Using Passive Sensors
        - Field Test 4B: Testing Freezing Point Using Active Sensors
    - Field Test 5: Ice Bath at 32º F
    - Field Test 6: Pavement Temperature Forced Below Freezing
- Do you have any suggestions to improve the tests? Are there any difficult steps?
    - Field Test 1: Frost Condition
    - Field Test 2: Pavement Temperature at Ambient Conditions
    - Field Test 3: Pavement Surface Dry/Wet/Ice Conditions
    - Field Test 4: Freezing Point of Passive and Active Pavement Sensors
        - Field Test 4A: Testing Freezing Point Using Passive Sensors
        - Field Test 4B: Testing Freezing Point Using Active Sensors
    - Field Test 5: Ice Bath at 32º F
    - Field Test 6: Pavement Temperature Forced Below Freezing
- Did you find the tests to be physically demanding?
- How confident are you that the data was accurate?

Evaluate training and guidelines

- Was the training instruction clear?
    - Video
    - Pictures
    - Text
- Were the guidelines clear?
- Was there enough explanation during the training?
- Would you have been able to conduct tests without training?
- Are you confident enough in the results that you would call your supervisor to report a defective sensor? Are you confident enough to call a vendor?
- Did you mix the solution concentrations?
    - Which solutions did you mix?
    - Did you have the necessary equipment available to mix the solutions?
    - Were the text instructions clear enough to make the solutions?

Personal Information

- How does your agency affect your experience
- Title
- Gender
- Age
- Highest level of education
    - HS graduate/some
    - Technical degree/some
    - College degree/some
- How much experience do you have with computers
    - PC at home
    - Internet at home? Email? How often
    - PC at work
    - Internet at work? Email? How often
    - Do you use a PDA
- Rate yourself in math (below average, average, above average)
- Rate yourself in science (below average, average, above average

APPENDIX J
FIELD TEST DATA

Frost Test Data

	MN-Sensor A			NV-Sensor B			PA-Sensor D
	Tech 1	**Tech 2**	**Tech 3**	**Tech 1**	**Tech 2**	**Tech 3**	**Tech 1**
Time of Day	9:05 AM	9:30 AM	10:05 AM	8:30 AM	8:06 AM	8:06 AM	8:00 AM
Air Temperature	7.8	7.8	N/A	37.2	35.1	31.8	33.4
Pavement Temperature	N/A	12.8	N/A	38.1	35.2	33.1	34.2
Dew Point Temperature	N/A	2.5	N/A	33.4	32.2	28.9	25.6
Surface State Visual Observation	Wet	Clean	No Frost	Dry	Clear	Dry	Dry
Surface State Sensor Reading	Chem Wet 95	Dry	Dry	21	31	31	Dry
Surface State (from RPU)	Chem Wet 95	Dry	Dry	Dry	Dry	Dry	Dry

Field Test 2 - Ambient Pavement Temperature
Minnesota

Tech 1 (Run 1/3)

		Pavement Sensor	Thermistor (on sensor)	IR Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading (2.5" from sensor)
1	9:23	30.03	30.70	27.7	28.30	24.2
2	9:28	29.87	30.25	27.5	28.06	26.5
3	9:33	29.72	30.03	27.1	28.00	26.7
4	9:36	29.56	29.88	27.6	27.97	25.6
5	9:38	29.41	29.74	27.2	27.95	25.4
6	9:41	29.41	29.62	26.4	27.94	25.4

Tech 1 (Run 2/3)

		Pavement Sensor	Thermistor (on sensor)	IR Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading (2.5" from sensor)
1	9:50	29.72	30.70	29.8	38.75	26
2	9:52	29.72	30.25	30.3	28.64	25.9
3	9:54	29.56	30.12	31.7	28.61	26.4
4	9:56	29.56	30.01	27.2	28.61	26.1
5	9:59	29.41	29.87	29.9	28.53	26.4
6	10:02	29.41	29.81	31.6	28.51	27.4
7	10:08	29.41	29.80	30.7	28.53	27.2
8	10:11	29.41	29.81	30.6	28.53	27.4

Tech 1 (Run 3/3)

		Pavement Sensor	Thermistor (on sensor)	IR Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading (2.5" from sensor)
1	10:17	29.82	30.14	29	29.22	27.4
2	10:19	29.72	30.06	28.9	29.05	27.2
3	10:21	29.72	30.04	29	28.98	27.2
4	10:23	29.56	30.03	28.5	28.95	27.3
5	10:25	29.67	30.05	29.5	28.95	27
6	10:27	29.82	30.02	28.9	28.88	27.1
7	10:29	29.82	30.02	28.4	28.92	27
8	10:31	29.82	30.07	28.8	28.97	27
9	10:33	29.82	30.09	29.1	28.99	27
10	10:35	29.72	30.11	28.1	29	27

Tech 2 (Run 1/2)

		Pavement Sensor	Thermistor (on sensor)	IR Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading (2.5" from sensor)
1	10:10	15.28	16.02	12.5	13.27	11.4
2	10:13	15.28	15.59	12.5	13.33	11.9
3	10:19	14.97	15.32	12.7	13.35	11.5
4	10:23	14.82	15.20	12.3	13.46	11.4
5	10:25	14.77	15.18	12.3	13.50	11.6
6	10:28	14.93	15.13	12.3	13.55	11.7

Tech 2 (Run 2/2)

		Pavement Sensor	Thermistor (on sensor)	IR Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading (2.5" from sensor)
1	10:41	15.24	15.54	13.8	14.03	12.7
2	10:43	15.24	15.54	14.4	14.09	15
3	10:48	15.13	15.45	17.9	14.12	16.9
4	10:51	15.24	15.41	17.7	14.16	16.8

Tech 3 (Run 1/1)

		Pavement Sensor	Thermistor (on sensor)	IR Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading (2.5" from sensor)
1	10:47	22.99	23.10	Not Available	Not Performed	Not Available
2	10:50	22.99	23.19	24	Not Performed	Not Available
3	10:54	23.14	23.26	24.3	Not Performed	23.3
4	10:56	23.14	23.40	24.7	Not Performed	23.5
5	10:59	23.30	23.45	24.7	Not Performed	23.5
6	11:01	23.30	23.47	24.3	Not Performed	23.3

Field Test 2 - Ambient Pavement Temperature
Nevada

Tech 1 Run 1

Time		Pavement Sensor Reading	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
8:52	1	39.2	41.23	39.76	33.6	32.2	42.1	42.0
8:54	2	39.2	41.23	39.78	34.3	32.3	42.3	41.7
8:56	3	39.2	41.23	39.81	36.0	32.6	42.2	41.9
8:58	4	39.4	41.23	39.83	34.2	32.7	42.0	41.7
9:00	5	39.4	41.22	39.85	33.9	32.5	42.2	41.7
9:02	6	39.4	41.27	39.88	34.4	32.0	42.1	41.8
9:04	7	39.4	41.27	39.92	33.6	32.0	42.3	41.8
9:06	8	39.6	41.32	39.92	34.3	32.8	42.3	41.9
9:08	9	39.4	41.38	39.96	34.9	32.4	42.5	41.9
9:10	10	39.6	41.41	39.97	35.0	33.2	42.6	42.1

Tech 1 Run 2

Time		Pavement Sensor Reading	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
9:26	1	40.5	41.13	40.06	37.7	35.5	43.5	42.5
9:28	2	40.5	41.13	40.06	36.9	35.3	43.5	42.8
9:30	3	40.5	41.11	40.08	36.5	35.0	43.5	42.8
9:32	4	40.5	41.07	40.08	36.2	34.5	43.3	42.4
9:34	5	40.5	41.09	40.10	36.0	34.4	43.3	42.5
9:36	6	40.5	41.07	40.12	36.1	35.0	43.0	42.5
9:38	7	40.5	41.09	40.14	35.8	35.3	43.3	42.6
9:40	8	40.5	41.09	40.15	36.0	35.2	43.4	42.8
9:42	9	40.5	41.09	40.15	36.3	35.0	43.2	42.5
9:44	10	40.5	41.07	40.17	36.0	35.6	43.4	42.7

Tech 2 Run 1

Time		Pavement Sensor Reading	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
8:26	1	36.1	38.44	36.90	32.5	32.4	38.5	37.9
8:28	2	36.1	38.43	36.90	32.5	32.1	38.4	37.9
8:30	3	36.3	38.43	36.93	33.1	34.0	38.5	38.3
8:32	4	36.3	38.48	36.97	33.1	33.2	38.5	38.1
8:34	5	36.3	38.48	37.02	33.2	33.2	38.5	38.0
8:36	6	36.3	38.41	37.00	33.4	33.4	38.8	38.1
8:38	7	36.5	38.44	37.06	33.5	33.5	38.7	38.1
8:40	8	36.5	38.44	37.08	33.7	33.5	38.7	38.2
8:42	9	36.3	38.52	37.09	33.9	34.6	38.7	38.4
8:44	10	36.3	38.48	37.09	34.6	35.5	38.8	38.4

Tech 1 Run 2

Time		Pavement Sensor Reading	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
8:58	1	36.7	38.68	37.33	35.3	36.3	39.4	38.9
9:00	2	36.7	38.70	37.36	35.3	34.7	39.4	39.1
9:02	3	36.7	38.68	37.38	35.5	35.2	39.3	39.2
9:04	4	36.9	38.71	37.42	35.1	34.4	39.6	39.1
9:06	5	36.9	38.71	37.44	35.2	34.4	40.1	40.1
9:08	6	36.7	38.66	37.44	35.2	34.3	39.5	39.1
9:10	7	36.9	38.68	37.47	35.3	34.8	39.6	39.2
9:12	8	36.9	38.77	37.53	35.1	35.1	39.7	39.3
9:14	9	36.9	38.75	37.53	35.7	35.1	39.6	39.3
9:16	10	36.9	38.84	37.58	35.6	35.1	39.7	39.3

Tech 3 Run 1

Time		Pavement Sensor Reading	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
8:30	1	34.7	35.69	35.28	33.7	33.6	37.6	36.9
8:32	2	34.9	35.74	35.35	33.8	33.7	37.5	37.1
8:34	3	34.9	35.82	35.42	33.6	33.6	37.4	37.4
8:36	4	35.1	35.89	35.47	33.6	33.6	37.8	37.6
8:38	5	35.1	35.96	35.56	33.7	33.7	37.9	37.6
8:40	6	35.2	36.03	35.62	33.9	33.6	38.0	37.8
8:42	7	35.2	36.10	35.69	33.8	33.8	38.0	37.7
8:44	8	35.4	36.16	35.74	33.7	33.8	38.2	37.7
8:46	9	35.4	36.23	35.82	33.9	34.0	38.4	38.0
8:48	10	35.6	36.28	35.87	33.9	34.1	38.5	38.0

Tech 3 Run 1

Time		Pavement Sensor Reading	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
9:06	1	36.7	36.41	36.50	33.9	34.4	39.9	39.1
9:08	2	36.9	36.45	36.57	33.8	34.0	39.8	39.0
9:10	3	36.9	36.48	36.61	33.7	34.0	39.5	39.0
9:12	4	36.9	36.54	36.68	33.8	34.1	40.0	39.2
9:14	5	37.0	36.59	36.73	34.1	34.2	40.0	39.2
9:16	6	37.0	36.70	36.84	33.7	34.0	40.1	39.3
9:18	7	37.2	36.70	36.86	34.2	34.2	40.1	39.5
9:20	8	37.4	36.77	36.93	34.2	34.2	40.4	39.7
9:22	9	37.4	36.81	36.99	34.2	34.2	40.5	39.6
9:24	10	37.6	36.88	37.06	34.2	34.2	40.5	39.7

Field Test 2 - Pennsylvania State Visit
Pavement Temperature Test

Tech 1 March 22, 2005
1 of 2

Time		Pavement Sensor Reading (°F)	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
9:43	1	36	39.7	36.7	38.0	34.2	41.7	38.8
9:45	2	36	39.7	36.7	37.9	34.1	41.7	38.8
9:47	3	36	39.6	36.7	37.6	33.9	41.5	38.7
9:49	4	36	39.5	36.7	37.6	33.9	41.7	38.9
9:51	5	36	39.5	36.7	37.8	34.1	41.7	38.9
9:53	6	36	39.5	36.7	37.5	34.1	41.7	39.1
9:55	7	36	39.4	36.7	37.8	34.2	41.9	39.3
9:57	8	36	39.4	36.7	38.0	34.1	42.0	39.3
9:59	9	36	39.4	36.7	37.9	34.2	41.9	39.1
10:01	10	36	39.3	36.8	37.4	33.9	41.9	39.2

Tech 1 March 22, 2005
2 of 2

Time		Pavement Sensor Reading (°F)	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
10:32	1	36	40.3	37.4	40.2	36.1	42.5	39.6
10:34	2	36	40.2	37.4	38.9	34.9	42.5	39.8
10:36	3	36	40.1	37.4	37.5	33.8	42.6	39.9
10:38	4	36	40.1	37.4	37.0	33.7	42.5	39.8
10:40	5	36	40.0	37.5	37.0	33.6	42.6	40.0
10:42	6	36	40.0	37.5	37.8	34.2	42.5	39.8
10:44	7	36	39.9	37.5	37.4	34.0	42.5	39.9
10:46	8	36	39.9	37.5	38.0	34.7	42.7	40.1
10:48	9	36	39.9	37.6	38.6	35.0	43.0	40.1
10:50	10	36	39.8	37.6	39.1	35.0	43.1	40.1

Tech 2 March 22, 2005
1 of 2

Time		Pavement Sensor Reading (°F)	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
12:28	1	36	45.2	39.7	42.8	37.3	46.9	42.7
12:30	2	36	45.0	39.7	42.5	37.3	46.8	42.9
12:32	3	36	44.9	39.7	42.6	36.7	46.9	42.6
12:34	4	36	44.8	39.7	42.6	36.4	46.9	42.7
12:36	5	36	44.7	39.7	42.5	36.5	47.0	42.8
12:38	6	36	44.6	39.6	42.4	36.4	46.8	42.9
12:40	7	36	44.4	39.6	42.3	36.5	47.0	42.6
12:42	8	36	44.3	39.6	41.9	36.3	46.9	43.0
12:44	9	36	44.2	39.6	42.1	36.5	46.8	42.6
12:46	10	36	44.1	39.6	42.0	36.4	46.5	42.7

Tech 2 March 22, 2005
2 of 2

Time		Pavement Sensor Reading (°F)	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
13:17	1	37	43.07	39.58	40.1	34.7	46.3	42.5
13:19	2	37	42.93	39.55	40.0	34.8	46.1	42.5
13:21	3	37	42.86	39.56	39.9	34.9	46.1	42.8
13:23	4	37	42.76	39.55	40.6	35.3	46.3	42.6
13:25	5	37	42.68	39.55	40.5	35.2	46.3	42.5
13:27	6	37	42.61	39.54	40.2	35.3	46.2	42.5
13:29	7	37	42.54	39.55	40.2	35.5	46.5	42.6
13:31	8	37	42.46	39.55	40.8	36.0	46.2	42.5
13:33	9	37	42.42	39.60	41.2	36.2	46.0	42.6
13:35	10	37	42.37	39.58	40.8	36.2	46.1	42.8

Field Test 2 - Ambient Pavement Temperature
Pennsylvania

Tech 1 March 23, 2005
1 of 2

Time		Pavement Sensor Reading (°F)	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
10:11	1	35.3	35.8	35.9	32.9	32.7	37.4	37.4
10:13	2	35.3	35.8	35.9	32.2	32.1	37.5	37.3
10:15	3	35.3	35.8	35.9	31.7	31.5	37.5	37.2
10:17	4	35.3	35.8	35.9	31.5	31.1	37.2	37.2
10:19	5	35.3	35.7	35.9	31.5	31.0	37.3	37.2
10:21	6	35.1	35.7	35.8	31.4	31.2	37.1	37.0
10:24	7	35.1	35.7	35.8	31.2	31.1	37.1	37.0
10:26	9	35.1	35.7	35.8	31.5	31.2	37.1	37.0
10:28	10	35.1	35.7	35.8	31.6	31.4	37.3	37.0

Tech 1 March 23, 2005
2 of 2

Time		Pavement Sensor Reading (°F)	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
11:38	1	34.8	35.3	35.5	32.4	32.6	36.6	36.6
11:40	2	34.8	35.3	35.6	32.4	32.5	36.4	36.5
11:42	3	34.7	35.2	35.6	32.4	32.4	36.5	36.3
11:44	4	34.7	35.2	35.6	32.5	32.8	36.3	36.4
11:47	5	34.6	35.2	35.5	32.4	32.7	36.3	36.3
11:49	6	34.6	35.1	35.5	32.7	32.8	36.6	36.3
11:51	7	34.5	35.1	35.5	32.6	32.8	36.1	36.2
11:53	8	34.5	35.1	35.5	32.8	32.9	36.1	36.3
11:55	9	34.5	35.1	35.4	32.6	32.8	36.1	36.2
12:00	10	34.5	35.0	35.4	32.5	32.8	36.1	36.3

Tech 2 March 23, 2005
1 of 2

Time		Pavement Sensor Reading (°F)	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
10:52	1	35.3	35.85	35.88	34.0	33.9	37.3	36.9
10:54	2	35.2	35.84	35.87	33.7	33.7	37.1	37.1
10:56	3	35.2	35.84	35.87	34.0	33.8	37.1	37.1
10:59	4	35.2	35.83	35.80	34.0	33.8	37.5	36.9
11:01	5	35.1	35.80	35.83	33.9	33.8	37.4	36.9
11:03	6	35.1	35.78	35.82	34.6	33.8	37.3	36.8
11:05	7	35.1	35.77	35.81	34.5	33.8	37.2	37.0
11:07	8	35.1	35.75	35.78	34.2	33.8	37.1	36.8
11:09	9	35.1	35.72	35.75	34.2	33.6	37.1	36.6
11:12	10	35.1	35.68	35.72	34.0	33.6	37.1	36.5

Tech 2 March 23, 2005
2 of 2

Time		Pavement Sensor Reading (°F)	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
12:28	1	34.3	34.90	35.11	34.8	34.3	36.7	36.5
12:30	2	34.3	34.92	35.10	34.6	34.2	36.7	36.6
12:32	3	34.3	34.92	35.09	34.2	34.0	36.6	36.4
12:34	4	34.3	34.89	35.07	34.2	34.0	36.5	36.4
12:37	5	34.3	34.89	35.06	34.1	34.0	36.4	36.4
12:39	6	34.3	34.88	35.05	34.2	33.9	36.5	36.4
12:41	7	34.3	34.89	35.04	34.2	33.7	36.4	36.4
12:43	8	34.3	34.89	35.05	34.0	33.6	36.6	36.4
12:45	9	34.3	34.88	35.04	33.9	33.5	36.6	36.3
12:47	10	34.3	34.88	35.03	33.8	33.5	36.6	36.3

Field Test 3 - Minnesota State Visit

Surface State Test (Minnesota)

Tech 1	Time Condition Was Applied	Visual Observation	RPU Surface Status	Water Thickness
	13:55	Dry	Dry	Not Recorded
	14:02	Wet	Dry	Not Recorded
	14:07	Wet	Damp	Not Recorded

Tech 2	Time Condition Was Applied	Visual Observation	RPU Surface Status	Water Thickness
	11:21	Dry	Dry	Not Recorded
	11:28	Wet	Damp	0.5 mm
	11:47	Frozen	Watch	0.5 mm

Tech 3	Time Condition Was Applied	Visual Observation	RPU Surface Status	Water Thickness
	11:03	Dry	Dry	Not Recorded
	11:09	Wet	Not Recorded	< 1 mm
	11:10	Frozen	Not Recorded	1 mm
	11:28	Wet	Not Recorded	Full well

Field Test 3 - Nevada State Visit

Surface State Test

Tech 1	Local Time of Day	Visual Observation	Pavement Surface State Code, item 36	Surface Status	Water Thickness, item 42	Concentration g/l. item 39	
	9:50	dry	21	Cloudy Dry	0.00	0.0	
Applied Tap Water							
	9:52	wet	31	Clear Dry	0.00	0.0	
	9:54	wet	32	Clear Moist	0.00	0.0	RPU reported **"moist"** less than **4** minutes after applying water
Dried sensor surface with paper towel							
	9:56	dry	32	Clear Moist	0.00	0.0	
	9:58	dry	32	Clear Moist	0.00	0.0	
	10:00	dry	31	Clear Dry	0.00	0.0	RPU reported **dry** less than **6** minutes after drying with paper towel
	10:02	dry	31	Clear Dry	0.00	0.0	
	10:04	dry	21	Cloudy Dry	0.00	0.0	
Applied Tap Water							
	10:06	wet	31	Clear Dry	0.00	0.0	
	10:08	wet	32	Clear Moist	0.00	0.0	
	10:10	wet	32	Clear Moist	0.00	0.0	
	10:12	wet	33	Clear Wet	0.03	0.0	RPU reported **wet** less than **8** minutes after applying water

Tech 2	Local Time of Day	Visual Observation	Pavement Surface State Code, Item 36	Surface Status	Water Thickness, item 42	Concentration g/l. item 39	
	9:26	dry	31	Clear Dry	0.00	0.0	
Added tap water-soaked paper towel							
	9:28	wet	31	Clear Dry	0.00	0.0	
	9:30	wet	33	Clear Wet	0.07	0.0	RPU reported **wet** less than **4** minutes after applying water
	9:32	wet	33	Clear Wet	0.14	0.0	
	9:34	wet	33	Clear Wet	0.23	0.0	
Removed wet paper towel, dried sensor surface with paper towel							
	9:36	dry	33	Clear Wet	0.32	0.0	
Dried sensor surface with paper towel again							
	9:38	dry	33	Clear Wet	0.40	0.0	
	9:40	dry	33	Clear Wet	0.42	0.0	
	9:42	dry	33	Clear Wet	0.41	0.0	
	9:44	dry	33	Clear Wet	0.36	0.0	
	9:46	dry	33	Clear Wet	0.29	0.0	
	9:48	dry	32	Clear Moist	0.23	0.0	
	9:50	dry	22	Cloudy Mois	0.17	0.0	
	9:52	dry	22	Cloudy Mois	0.13	0.0	
	9:54	dry	32	Clear Moist	0.10	0.0	
Dried sensor surface with heat gun							
	9:56	dry	32	Clear Moist	0.08	0.0	
	9:58	dry	32	Clear Moist	0.06	0.0	
Dried sensor surface with heat gun again							
	10:00	dry	31	Clear Dry	0.05	0.0	RPU reported **dry** less than **6** minutes after using the heat gun
	10:02	dry	31	Clear Dry	0.04	0.0	
Added tap water-soaked paper towel							
	10:04	wet	31	Clear Dry	0.03	0.0	RPU reported **wet** less than **2** minutes after applying water
	10:06	wet	32	Clear Moist	0.02	0.0	
	10:08	wet	33	Clear Wet	0.08	0.0	

Tech 3	Local Time of Day	Visual Observation	Pavement Surface State Code, item 36	RPU Surface Status	Water Thickness, item 42	Concentration g/l. item 39	
	9:37	dry	31	Clear Dry	0.00	0.0	
	9:39	dry	31	Clear Dry	0.00	0.0	
	9:41	dry	31	Clear Dry	0.00	0.0	
Added tap water-soaked paper towel							
	9:43	wet	31	Clear Dry	0.00	0.0	
	9:45	wet	32	Clear Moist	0.07	0.0	
	9:47	wet	33	Clear Wet	0.16	0.0	RPU reported **wet** less than **6** minutes after applying water
	9:49	wet	33	Clear Wet	0.26	0.0	
Removed wet paper towel, dried sensor surface with paper towel							
	9:51	dry	33	Clear Wet	0.35	0.0	
	9:53	dry	33	Clear Wet	0.37	0.0	
	9:55	dry	33	Clear Wet	0.35	0.0	
	9:57	dry	33	Clear Wet	0.28	0.0	
	9:59	dry	33	Clear Wet	0.22	0.0	
	10:01	dry	32	Clear Moist	0.17	0.0	
	10:03	dry	32	Clear Moist	0.13	0.0	
	10:05	dry	32	Clear Moist	0.10	0.0	
	10:07	dry	32	Clear Moist	0.08	0.0	
	10:09	dry	32	Clear Moist	0.06	0.0	
Dried sensor surface with heat gun							
	10:11	dry	32	Clear Moist	0.04	0.0	
	10:13	dry	31	Clear Dry	0.03	0.0	RPU reported **dry** less than **4** minutes after using the heat gun
	10:15	dry	31	Clear Dry	0.03	0.0	
Added tap water-soaked paper towel							
	10:17	wet	31	Clear Dry	0.02	0.0	
	10:19	wet	32	Clear Moist	0.08	0.0	
	10:21	wet	33	Clear Wet	0.17	0.0	RPU reported **wet** less than **6** minutes after applying water
	10:23	wet	33	Clear Wet	0.29	0.0	

Field Test 3 - Pennsylvania State Visit

Surface State Test

Tech 1	Local Time of Day	Visual Observation	RPU Surface Status	Chemical Index	Notes
	11:02	dry	dry	0	
Applied tap water to sensor surface					
	11:04	wet	dry	0	
	11:06	wet	chemically wet	32	RPU Reported **wet** less than **4** minutes after applying water
	11:08	wet	chemically wet	32	
Dried sensor surface with heat gun					
	11:16	dry	dry	0	RPU Reported **dry** less than **8** minutes after heat gun was used
	11:18	dry	dry	0	
Applied tap water to sensor surface					
	11:20	wet	dry	0	
	11:22	wet	chemically wet	22	RPU Reported **wet** less than **4** minutes after applying water
	11:24	wet	chemically wet	25	
Dried sensor surface with heat gun					
	11:26	dry	chemically wet	26	
	11:28	dry	dry	0	RPU Reported **dry** less than **4** minutes after heat gun was first used
	11:30	dry	dry	0	
Applied tap water to sensor surface					
	11:32	wet	dry	0	
	11:34	wet	chemically wet	32	RPU Reported **wet** less than **4** minutes after applying water
	11:36	wet	chemically wet	33	
	11:38	wet	chemically wet	32	
	11:40	wet	chemically wet	32	
Dried sensor surface with heat gun					
	11:42	dry	chemically wet	31	RPU Reported **dry** less than **2** minutes after heat gun was first used
	11:44	dry	dry	0	

Tech 2	Local Time of Day	Visual Observation	Surface Status	Chemical Index	
	11:51	dry	dry	0	
Applied tap water to sensor surface					
	11:55	wet	wet	48	RPU Reported **wet** less than **4** minutes after applying water
	11:57	wet	wet	52	
Dried sensor surface with heat gun					
	11:59	dry	dry	0	RPU Reported **dry** less than **2** minutes after heat gun was first used
	12:01	dry	dry	0	
Applied tap water to sensor surface					
	12:03	wet	wet	24	RPU Reported **wet** less than **2** minutes after applying water
	12:05	wet	wet	26	
Dried sensor surface with heat gun					
	12:07	dry	dry	0	RPU Reported **dry** less than **2** minutes after heat gun was first used
Applied tap water to sensor surface					
	12:09	wet	wet	36	RPU Reported **wet** less than **2** minutes after applying water
	12:11	wet	wet	37	

Field Test 3 - Pennsylvania State Visit

Surface State Test

Jeff	23-Mar-05		
Local Time of Day	**Visual Observation**	**RPU Surface Status**	
1:00	dry	dry	
Applied tap water to sensor surface			
1:05	wet	wet	RPU Reported **wet** less than **5** minutes after applying water
1:17	wet	wet	
Dried sensor surface with heat gun			
1:24	dry	dry	RPU Reported **dry** less than **7** minutes after applying water
Applied tap water to sensor surface			
1:26	wet	wet	RPU Reported **wet** less than **2** minutes after applying water
1:27	wet	wet	
Dried sensor surface with heat gun			
1:29	dry	dry	RPU Reported **dry** less than **2** minutes after applying water
1:31	dry	dry	
Applied tap water to sensor surface			
1:35	wet	wet	RPU Reported **wet** less than **4** minutes after applying water
1:37	dry	dry	

Field Test 4 - Freezing Point
Minnesota

4%

	Tech 1 (Run 1/2)	Tech 1 (Run 2/2)	Tech 2	Tech 3
	Run 1	Run 2	Run 3	Run 4
Reading	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)
0				
1	28.02	27.99	28.00	27.99
2	28.03	28.02	28.00	28.08
3	28.04	28.03	28.00	28.06

10%

	Tech 1 (Run 1/2)	Tech 1 (Run 2/2)	Tech 2	Tech 3
	Run 1	Run 2	Run 3	Run 4
Reading	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)
0				
1	21.41	21.19	21.54	21.36
2	21.49	21.29	21.55	21.85
3	21.59	21.43	21.44	21.89
4	21.53	21.39	21.47	
			21.47	

15%

	Tech 1 (Run 1/2)	Tech 1 (Run 2/2)	Tech 2	Tech 3
	Run 1	Run 2	Run 3	Run 4
Reading	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)
0				
1	15.92	15.68	15.51	15.73
2	16.17	15.45	15.57	16.10
3	16.02	15.72	15.59	16.05
4	16.00	15.60	15.90	15.99
5				

Saturated

	Tech 1 (Run 1/2)	Tech 2	
	Run 1	Run 2	Run 3
Reading	Freezing Point (F)	Freezing Point (F)	
0			
1	7.43	6.62	
2	8.08	8.13	
3	7.72	8.13	
4	8.44	7.20	
5		7.30	
6		7.33	
7		7.34	

Test 4 - Freezing Point All Temperatures in Celsius
Nevada

1%

Reading	A	B	C	D	Baseline
1	-0.8	-3.1	-1.2	-1.4	-0.59
2	-0.9	-3.4	-1.2	-1.5	-0.59
3	-1.0	-3.6	-1.3	-1.5	-0.59
4	-1.1	-3.7	-1.3	-1.6	-0.59
5	-1.2	-3.8	-1.3	-1.6	-0.59
6	-0.7	-3.9	-1.4	-1.6	-0.59
7	-0.5	-3.9	-1.4	-1.5	-0.59
8	-0.3	-3.8	-1.4	-1.5	-0.59
9	-0.2	-3.8	-1.4	-1.4	-0.59
10	-0.2	-3.7	-1.4	-1.3	-0.59

4%

Reading	A	B	C	D	E	F	Baseline
1	-1.6	-3.2	-6.3	-2.7	-0.7	-1.8	-2.4
2	-1.2	-3.7	-6.6	-2.5	-0.6	-2.0	-2.4
3	-1.2	-4.1	-6.8	-2.4	-0.8	-2.2	-2.4
4	-1.2	-4.6	-6.9	-2.3	-1.0	-1.3	-2.4
5	-1.2	-4.9	-7.0	-2.2	-1.0	-1.1	-2.4
6	-1.2	-5.2	-7.1	-2.2	-0.9	-10	-2.4
7	-1.3	-5.4	-7.1	-2.1	-0.9	-1.0	-2.4
8	-1.4	-5.6	-7.2	-2.1	-0.9	-1.0	-2.4
9	-1.4	-5.7	-7.2	-2.1	-0.9	-1.0	-2.4
10	-1.5	-5.7	-7.2	-2.1	-0.9	-1.0	-2.4

10%

Reading	A	B	C	D	Baseline
1	-9.2	-11.5	-9.9	-1.5	-6.6
2	-9.5	-11.2	-11.3	-1.5	-6.6
3	-9.7	-11.0	-12.9	-2.5	-6.6
4	-9.8	-10.9	-14.7	-2.5	-6.6
5	-10.0	-10.9	-16.5	-3.0	-6.6
6	-10.1	-10.8	-18.3	-3.5	-6.6
7	-10.2	-10.8	-20.2	-3.9	-6.6
8	-10.2	-10.8	-21.1	-4.8	-6.6

9	-10.3	-10.9	-21.1	-5.3	-6.6
10	-10.4	-10.9	-21.1	-5.3	-6.6

15% Reading	**A**	**Baseline**
1	-13.8	-10.9
2	-14.2	-10.9
3	-14.6	-10.9
4	-14.9	-10.9
5	-15.2	-10.9
6	-15.5	-10.9
7	-15.7	-10.9
8	-15.8	-10.9
9	-16.0	-10.9
10	-16.1	-10.9

Field Test 4 - Freezing Point

Pennsylvania State Visit

Tech 1

Time	FP	Solution	Solution FP
8:02	23.1	10%	20.2
Flushed sensor with distilled water			
8:11	32.0	distilled water	32.0
Applied 10% NaCl brine to sensor			
8:19	23.1	10%	20.2
8:28	23.1	10%	20.2

Tech 2

Time	FP	Solution	
9:01	22.2	10%	20.2
9:09	22.0	10%	20.2

Additional Tests

Time	FP	Solution	
Applied 10% NaCl brine to sensor			
10:13	22.2	10%	20.2
10:15	21.5	10%	20.2
Applied 4% NaCl brine to sensor			
10:19	28.0	4%	27.7
10:28	28.7	4%	27.7
10:37	28.7	4%	27.7
10:48	28.7	4%	27.7
10:59	28.4	4%	27.7
11:09	28.3	4%	27.7
11:18	28.4	4%	27.7
11:31	28.5	4%	27.7
11:42	28.5	4%	27.7
11:53	28.5	4%	27.7
12:00	28.7	4%	27.7

Field Test 5 - Ice Bath

Minnesota

Time of Day	Tech 1 (Pavement Sensor)	Tech 1 (Thermistor)
2:20	33.42	32.20
2:22	33.21	32.03
2:24	32.64	31.99
2:27	32.49	31.96
2:29	32.44	31.94
2:31	32.34	31.93

Time of Day	Tech 2 (Pavement Sensor)	Tech 2 (Thermistor)
2:18	32.00	31.93
2:20	32.00	31.89
2:22	31.77	31.86
2:23	31.62	31.85

Time of Day	Tech 3 (Pavement Sensor)	Tech 3 (Thermistor)
1:38	34.55	33.00
1:40	34.24	32.84
1:42	33.62	32.27
1:44	33.01	32.05
1:46	32.54	32.02
1:48	32.39	31.98
1:50	32.24	31.92
1:52	32.08	31.88
1:54	32.08	31.83
1:56	31.93	31.80
1:58	31.77	31.75
2:00	31.77	31.72

Field Test 5 - Ice Bath (All temperatures in Celsius)

Nevada

Tech 1	Pavement Sensor	Thermistor
1:56	6.5	1.26
1:58	4.8	1.02
2:00	3.7	0.7
2:02	2.9	0.46
2:04	2.3	0.43
2:06	2.0	0.39
2:08	1.7	0.25
2:10	1.5	0.22
2:12	1.3	0.16
2:14	1.2	0.13
2:16	1.1	0.12
2:18	0.9	0.11
2:20	0.9	0.11
2:22	0.9	0.09
2:24	0.8	0.08
2:26	0.7	0.08
2:28	0.6	0.07
2:30	0.6	0.07
2:32	0.9	0.43
2:34	0.8	0.16
2:36	0.8	0.07
2:38	0.6	0.05
2:40	0.6	0.06
2:42	0.5	0.05
2:44	0.5	0.05
2:46	0.5	0.05
2:48	0.4	0.05
2:50	0.4	0.05
2:52	0.4	0.05
2:54	0.4	0.04

Tech 2	Pavement Sensor	Thermistor
1:22		7.55
1:24		6.61
1:26		1.15
1:36		1.57
1:38		0.96
1:40	2.9	1.12
1:42	3.1	0.4
1:44	1.9	0.18
1:46	1.6	0.55
1:48	1.7	0.14
1:50	1.3	0.11
1:52	1.8	1.18
1:54	1.1	0.15
1:56	0.9	0.11
1:58	0.8	0.1
2:00	0.7	0.06
2:02	0.7	0
2:04	0.7	0.04
2:06	0.8	0.13
2:08	0.7	0.01
2:10	0.6	0.01

Tech 3	Pavement Sensor	Thermistor
1:28	14.5	2.65
1:30	6.1	1.18
1:32	2.7	0.61
1:34	2.7	0.58
1:36	1.9	0.45
1:38	1.9	0.29
1:40	1.7	0.17
1:42	1.4	0.07
1:44	1.4	0.06
1:46	1.2	0.04
1:48	1.2	0.04
1:50	1.1	0.05
1:52	1.0	0.04
1:54	0.9	0.04
1:56	0.8	0.05
1:58	0.8	0.03
2:00	0.8	0.07
2:02	0.7	0.05
2:04	0.6	0.04
2:06	0.6	0.05

Field Test 5 - Pennsylvania State Visit		
Ice Bath Test		**Sensor C**
Tech 1	Pavement Sensor Reading	Thermistor Output
1:50	37	33.27
1:52	37	33.61
1:54	37	32.49
1:56	37	32.14
1:58	37	32.16
2:00	37	32.09
2:02	37	32.05
2:04	37	32.05
2:10	37	32.22
2:18	37	32.28

Field Test 6 - Dry Ice	
Minnesota	
Time of Day	Pavement Sensor Temperature (F)
0	23.6
2	17.9
4	-14.78
6	-27.11
8	-33.6
10	-42.23
12	-42.99
14	-44.53
16	-45.71
18	-46.07

Field Test 6 - Dry Ice			
Nevada			
All temps in degrees Celsius			
Time Elapsed	**Tech 1**	**Tech 2**	**Tech 3**
0	36.32	39.2	44.96
2	24.62	35.42	34.34
4	0.68	18.5	8.06
6	-16.6	4.64	-11.02
8	-28.66	-4.54	-24.16
10	-37.3	-10.48	-32.8
12	-43.96	-15.16	-39.1
14	-32.26	-18.94	-43.78
16	-17.5	-22	-47.56
18	-6.34	-25.06	-50.44
20	2.12	-27.76	-52.24
22	8.96		

APPENDIX K
STATISTICAL ANALYSIS OF FIELD TEST DATA

Temperature Tests

1. MN-Sensor A

Ambient Temperature Field Tests

Standard Deviation of Variable Data Points

Name	**Run**	**Points**	**Pavement Sensor Reading**	**Thermistor Reading (on sensor)**	**Thermistor Reading (2.5" from sensor)**	**IR Reading OS-951 (on sensor)**	**IR Reading OS-951 (2.5" from sensor)**
Tech 1	1	6	0.25	0.39	0.14	0.48	0.90
Tech 1	2	8	0.14	0.31	0.05	1.41	0.63
Tech 1	3	10	0.09	0.04	0.09	0.40	0.15
Tech 2	1	6	0.22	0.34	0.11	0.16	0.19
Tech 2	2	4	0.05	0.07	0.05	2.15	1.97
Tech 3	1	6	0.14	0.15		0.30	0.12
Tech 3-Points			6.00	6.00		5.00	4.00
Note	Outliers - t-test						
Average			**0.15**	**0.22**	**0.09**	**0.82**	**0.66**

The t-test on Tech 1 and Thermistor at 2.5" From sensor

Outliner	38.75	
1	28.64	
2	28.61	
3	28.61	
4	28.53	
5	28.51	
6	28.53	
7	28.53	
Average	28.57	
Standard Deviation	0.052	$t_{0.05}$
The t-test	168.85	2.447
Reject		

The t-test o Tech 2 and IR reading

Outliner	13.80	
1	14.40	
2	17.90	
3	17.70	
Average	16.67	
Standard Deviation	1.97	$t_{0.05}$
The t-test	1.03	4.303
Accept		

The t-test o Tech 2 and IR reading 2.5" from sensor

Outliner	12.70	
1	15.00	
2	16.90	
3	16.80	
Average	16.23	
Standard Deviation	1.07	$t_{0.05}$
The t-test	2.34	4.303
Accept		

Error: Measurements from Testing Methods are Reference or Target or baseline
Average of variable points

Name	Run	Points	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)
Tech 1	1	6	0.37	1.63	2.42	4.03
Tech 1	2	8	0.46	0.93	1.46	2.81
Tech 1	3	10	0.31	0.76	0.93	2.63
Tech 2	1	6	0.40	1.60	2.58	3.43
Tech 2	2	4	0.27	1.11	1.88	1.53
Tech 3	1	6	0.37	1.63	2.42	4.03
Average			**0.36**	**1.21**	**1.85**	**2.89**

Accuracy Recommendation:

Since we use the absolute difference to analyze errors we note only deviations in one direction and ignore deviations in the other direction. Therefore, the one-tailed method is appropriate to establish the confidence limits. To find a one-tailed limit with confidence probability of 95% we want a normal deviate Z such that the area beyond Z in one tail is 0.05. In a normal distribution table the area from 0 to Z will be 0.45, and the value of Z is 1.645. A part from 5% chance in drawing the sample with the size of n:

average + 1.645 standard deviation / square root of n

To choose a fail/pass criteria we have three parameters to specify: average, standard deviation, and size of a sample.

In error analysis, 1.32F is the accuracy and 0.7F is the precision. Since the distribution of random errors follows the normal distribution with zero average and standard deviation from Gauss 1.32F indicates a systematic error and 0.7F is the random error.

If we assume the test will follow the same distribution (average and standard deviation) we can choose the number of samples to draw for the future test:

1.32 + 1.645 x 0.7 / 2.0 = 1.9 F for n=4

Difference between pavement sensor and Thermistor on sensor
Repeatability

	Tech 1	Tech 2
R1	0.46	0.35
	0.40	0.38
	0.39	0.41
	0.40	0.20
R2	0.20	0.30
	0.25	0.30
	0.27	0.32
	0.39	0.17
StDev1	0.03	0.09
StDev2	0.08	0.07
Average	0.06	0.08
Repeatability	0.31	0.45
Error Tolerance	1.05	1.51

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.039006	1	0.039006	7.438617	0.018355	4.747221
Columns	0.006806	1	0.006806	1.297974	0.276816	4.747221
Interaction	0.005256	1	0.005256	1.002384	0.336496	4.747221
Within	0.062925	12	0.005244			
Total	0.113994	15				
Repeatability	0.4					
Reproducibility	0.1					
Interaction	0.0					
R&R	0.4					
Error Tolerance	1.27					

Difference between pavement sensor and Thermistor from 2.5"
Repeatability

	Tech 1	Tech 2
R1	0.88	1.62
	0.90	1.36
	0.88	1.27
	0.88	1.38
R2	0.90	1.21
	0.85	1.15
	0.83	1.01
	0.72	1.08
StDev1	0.01	0.15
StDev2	0.08	0.09
Average	0.04	0.12
Repeatability	0.24	0.66
Error Tolerance	0.80	2.20

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.126	1	0.13	14.11	0.00	4.75
Columns	0.656	1	0.66	73.48	0.00	4.75
Interaction	0.055	1	0.06	6.18	0.03	4.75
Within	0.107	12	0.01			
Total	0.944	15				
Repeatability	0.5					
Reproducibility	1.4					
Interaction	0.6					
R&R	1.6					
Error Tolerance	5.31					

Difference between pavement sensor and IR reading
Repeatability

	Tech 1	Tech 2
R1	0.49	2.27
	2.19	2.52
	1.29	2.47
	1.19	2.63
R2	1.42	2.65
	1.02	1.99
	0.72	3.78
	1.62	3.54
StDev1	0.70	0.15
StDev2	0.40	0.83
Average	0.55	0.49
Repeatability	3.08	2.73
Error Tolerance	10.25	9.09

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.1785	1	0.1785	0.5279	0.4814	4.7472
Columns	8.8655	1	8.8655	26.2178	0.0003	4.7472
Interaction	0.3752	1	0.3752	1.1094	0.3130	4.7472
Within	4.0578	12	0.3381			
Total	13.4769	15				
Repeatability	2.8					
Reproducibility	0.0					
Interaction	5.7					
R&R	6.3					
Error Tolerance	21.15					

Difference between pavement sensor and IR reading from 2.5"
Repeatability

	Tech 1	Tech 2
R1	3.01	3.47
	2.01	3.42
	2.21	3.17
	2.01	3.23
R2	2.82	2.54
	2.82	0.24
	2.82	1.77
	2.72	1.56
StDev1	0.48	0.14
StDev2	0.05	0.96
Average	0.26	0.55
Repeatability	1.47	3.08
Error Tolerance	4.90	10.26

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	1.716	1	1.72	5.90	0.03	4.75
Columns	0.065	1	0.07	0.22	0.64	4.75
Interaction	5.198	1	5.20	17.86	0.00	4.75
Within	3.493	12	0.29			
Total	10.473	15				
Repeatability	3.0					
Reproducibility	5.3					
Interaction	0.0					
R&R	6.1					
Error Tolerance	20.31					

Ice Bath Field Tests

	Time of Day	Pavement Sensor	Thermistor	Convergence Index (Pavement Sensor)	Convergence Index (Thermistor)	Error
Tech 1	2:20	33.42	32.20			
	2:22	33.21	32.03	1.04	0.95	1.18
	2:24	32.64	31.99	1.02	1.02	
	2:27	32.49	31.96	1.02	1.06	
	2:29	32.44	31.94	1.01	1.09	
	2:31	32.34	31.93	1.01	1.11	
Tech 2	2:18	32.00	31.93			
	2:20	32.00	31.89	1.00	0.52	Outliner
	2:22	31.77	31.86	0.99	0.39	
	2:23	31.62	31.85	0.99	0.35	
Tech 3	1:38	34.55	33.00			
	1:40	34.24	32.84	1.07	0.48	
	1:42	33.62	32.27	1.05	0.83	
	1:44	33.01	32.05	1.03	0.97	0.96
	1:46	32.54	32.02	1.02	0.99	
	1:48	32.39	31.98	1.01	1.01	
	1:50	32.24	31.92	1.01	1.05	
	1:52	32.08	31.88	1.00	1.07	
	1:54	32.08	31.83	1.00	1.10	
	1:56	31.93	31.80	1.00	1.12	
	1:58	31.77	31.75	0.99	1.15	
	2:00	31.77	31.72	0.99	1.17	

Dry Ice Field Tests

Time of Day	Pavement Sensor Temperature	x	x*x
2:08	23.6	0	0
2:10	17.9	2	4
2:12	-14.78	4	16
2:14	-27.11	6	36
2:16	-33.6	8	64
2:18	-42.23	10	100
2:20	-42.99	12	144
2:22	-44.53	14	196
2:24	-45.71	16	256
2:26	-46.07	18	324

Linear Regression

SUMMARY OUTPUT				
Regression Statistics				
Multiple R	0.983517			
R Square	0.967306			
Adjusted R Square	0.957965			
Standard Error	5.405866			
Observations	10			
ANOVA				
	df	*SS*	*MS*	*F*
Regression	2	6052.403	3026.201	103.5541
Residual	7	204.5637	29.22338	
Total	9	6256.966		
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	26.66991	4.250337	6.274775	0.000414
X Variable 1	-10.3904	1.099699	-9.44838	3.11E-05
X Variable 2	0.362206	0.058815	6.1584	0.000464

2. NV-Sensor B

Ambient Temperature Field Tests
Standard Deviation of 10 Stable Data Points

Name	Run	Pavement Sensor Reading	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
Tech 1	1	0.1	0.07	0.07	0.73	0.37	0.18	0.14
Tech 1	2	0.0	0.02	0.04	0.57	0.39	0.16	0.15
Tech 2	1	0.1	0.03	0.08	0.63	0.99	0.14	0.18
Tech 2	2	0.1	0.05	0.08	0.21	0.58	0.22	0.32
Tech 3	1	0.3	0.21	0.20	0.12	0.18	0.37	0.36
Tech 3	2	0.3	0.16	0.19	0.22	0.13	0.32	0.28
Average		**0.2**	**0.09**	**0.11**	**0.41**	**0.44**	**0.23**	**0.24**

Note:
Temperature variation from pavement sensor is within 0.1 F so that it cannot tell the difference.

Error: Measurements from Testing Methods are Reference or Target or baseline;
Average of 10 stable points

Name	Run	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
Tech 1	1	1.92	0.51	4.94	6.89	2.90	2.49
Tech 1	2	0.63	0.35	4.11	5.38	2.88	2.15
Tech 2	1	2.13	0.68	2.97	2.78	2.29	1.82
Tech 2	2	1.93	0.66	1.46	1.85	2.80	2.47
Tech 3	1	0.84	0.43	1.39	1.40	2.78	2.43
Tech 3	2	0.46	0.32	3.11	2.94	2.99	2.24
Average		**1.32**	**0.49**	**3.00**	**3.54**	**2.77**	**2.27**

Difference between pavement sensor and Thermistor on sensor

Repeatability

	Tech 1	Tech 2	Tech 3
R1	2.03	2.30	0.99
	2.03	2.29	0.86
	2.03	2.11	0.94
	1.85	2.16	0.83
	1.84	2.16	0.90
	1.89	2.09	0.79
	1.89	1.94	0.86
	1.76	1.94	0.74
	2.00	2.20	0.81
	1.85	2.16	0.68
R2	0.67	2.00	0.27
	0.67	2.02	0.41
	0.65	2.00	0.38
	0.61	1.85	0.32
	0.63	1.85	0.45
	0.61	1.98	0.34
	0.63	1.82	0.52
	0.63	1.91	0.63
	0.63	1.89	0.59
	0.61	1.98	0.70
StDev1	0.10	0.12	0.09
StDev2	0.02	0.07	0.14
Average	0.06	0.10	0.12
Repeatability	0.31	0.51	0.62
Error Tolerance	1.05	1.72	2.07

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	5.818	1	5.82	589.77	0.00	4.02
Columns	19.118	2	9.56	968.97	0.00	3.17
Interaction	3.365	2	1.68	170.57	0.00	3.17
Within	0.533	54	0.01			
Total	28.834	59				
Repeatability	0.5					
Reproducibility	3.2					
Interaction	2.1					
R&R	3.9					
Error Tolerance	12.97					

Difference between pavement sensor and Thermistor on sensor after Calibration

Repeatability

	Tech 1	Tech 2	Tech 3
R1	0.80	0.77	0.63
	0.80	0.75	0.51
	0.80	0.57	0.58
	0.62	0.62	0.47
	0.60	0.62	0.54
	0.65	0.55	0.43
	0.65	0.41	0.50
	0.52	0.41	0.38
	0.76	0.66	0.45
	0.61	0.62	0.32
R2	0.16	0.84	0.27
	0.16	0.86	0.41
	0.17	0.84	0.38
	0.21	0.69	0.32
	0.19	0.69	0.45
	0.21	0.82	0.34
	0.19	0.66	0.52
	0.19	0.74	0.63
	0.19	0.73	0.59
	0.21	0.81	0.70
StDev1	0.10	0.12	0.09
StDev2	0.02	0.07	0.14
Average	0.06	0.10	0.12
Repeatability	0.31	0.51	0.63
Error Tolerance	1.05	1.71	2.09

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.191	1	0.19	19.27	0.00	4.02
Columns	0.715	2	0.36	36.04	0.00	3.17
Interaction	1.168	2	0.58	58.86	0.00	3.17
Within	0.536	54	0.01			
Total	2.611	59				
Repeatability	0.5					
Reproducibility	0.0					
Interaction	1.2					
R&R	1.3					
Error Tolerance	4.45					

Difference between pavement sensor and Thermistor from 2.5"
Repeatability

	Tech 1	Tech 2	Tech 3
R1	0.56	0.76	0.58
	0.58	0.76	0.47
	0.61	0.61	0.54
	0.45	0.65	0.41
	0.47	0.70	0.50
	0.50	0.68	0.38
	0.54	0.56	0.45
	0.36	0.58	0.32
	0.58	0.77	0.40
	0.41	0.77	0.27
R2	0.40	0.65	0.18
	0.40	0.68	0.29
	0.38	0.70	0.25
	0.38	0.56	0.18
	0.36	0.58	0.31
	0.34	0.76	0.20
	0.32	0.61	0.36
	0.31	0.67	0.47
	0.31	0.67	0.41
	0.29	0.72	0.52
StDev1	0.08	0.08	0.10
StDev2	0.04	0.06	0.12
Average	0.06	0.07	0.11
Repeatability	0.32	0.38	0.57
Error Tolerance	1.07	1.28	1.91

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.149	1	0.15	20.91	0.00	4.02
Columns	1.006	2	0.50	70.68	0.00	3.17
Interaction	0.046	2	0.02	3.25	0.05	3.17
Within	0.384	54	0.01			
Total	1.585	59				
Repeatability	0.4					
Reproducibility	0.8					
Interaction	0.0					
R&R	0.9					
Error Tolerance	3.03					

Difference between pavement sensor and IR reading
Repeatability

	Tech 1	Tech 2	Tech 3
R1	5.60	3.64	1.00
	4.90	3.64	1.08
	3.20	3.22	1.28
	5.18	3.22	1.46
	5.48	3.12	1.36
	4.98	2.92	1.34
	5.78	3.00	1.44
	5.26	2.80	1.72
	4.48	2.42	1.52
	4.56	1.72	1.70
R2	2.76	1.38	2.78
	3.56	1.38	3.06
	3.96	1.18	3.16
	4.26	1.76	3.06
	4.46	1.66	2.94
	4.36	1.48	3.34
	4.66	1.56	3.02
	4.46	1.76	3.20
	4.16	1.16	3.20
	4.46	1.26	3.38
StDev1	0.74	0.57	0.23
StDev2	0.57	0.22	0.18
Average	0.66	0.40	0.21
Repeatability	3.47	2.11	1.10
Error Tolerance	11.58	7.02	3.66

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.64	1	0.64	2.87	0.10	4.02
Columns	70.12	2	35.06	156.89	0.00	3.17
Interaction	29.11	2	14.56	65.14	0.00	3.17
Within	12.07	54	0.22			
Total	111.94	59				
Repeatability	2.4					
Reproducibility	5.2					
Interaction	6.2					
R&R	8.4					
Error Tolerance	28.11					

Difference between pavement sensor and IR reading from 2.5"
Repeatability

	Tech 1	Tech 2	Tech 3
R1	7.00	3.74	1.10
	6.90	4.04	1.18
	6.60	2.32	1.28
	6.68	3.12	1.46
	6.88	3.12	1.36
	7.38	2.92	1.64
	7.38	3.00	1.44
	6.76	3.00	1.62
	6.98	1.72	1.42
	6.36	0.82	1.50
R2	4.96	0.38	2.28
	5.16	1.98	2.86
	5.46	1.48	2.86
	5.96	2.46	2.76
	6.06	2.46	2.84
	5.46	2.38	3.04
	5.16	2.06	3.02
	5.26	1.76	3.20
	5.46	1.76	3.20
	4.86	1.76	3.38
StDev1	0.32	0.94	0.18
StDev2	0.39	0.62	0.30
Average	0.36	0.78	0.24
Repeatability	1.88	4.13	1.27
Error Tolerance	6.28	13.77	4.23

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	1.35	1	1.35	4.91	0.03	4.02
Columns	202.27	2	101.14	367.62	0.00	3.17
Interaction	26.34	2	13.17	47.88	0.00	3.17
Within	14.86	54	0.28			
Total	244.82	59				
Repeatability	2.7					
Reproducibility	10.8					
Interaction	5.8					
R&R	12.6					
Error Tolerance	41.92					

Difference between pavement sensor and IR Thermometer
Repeatability

	Tech 1	Tech 2	Tech 3
R1	2.90	2.36	2.90
	3.10	2.26	2.62
	3.00	2.18	2.52
	2.62	2.18	2.74
	2.82	2.18	2.84
	2.72	2.48	2.76
	2.92	2.20	2.76
	2.74	2.20	2.78
	3.12	2.38	2.98
	3.04	2.48	2.90
R2	3.04	2.72	3.22
	3.04	2.72	2.94
	3.04	2.62	2.64
	2.84	2.74	3.14
	2.84	3.24	2.96
	2.54	2.82	3.06
	2.84	2.74	2.88
	2.94	2.84	3.00
	2.74	2.74	3.10
	2.94	2.84	2.92
StDev1	0.17	0.12	0.14
StDev2	0.16	0.17	0.16
Average	0.16	0.15	0.15
Repeatability	0.87	0.77	0.79
Error Tolerance	2.90	2.58	2.63

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.817	1	0.82	34.45	0.00	4.02
Columns	1.542	2	0.77	32.52	0.00	3.17
Interaction	0.708	2	0.35	14.93	0.00	3.17
Within	1.280	54	0.02			
Total	4.346	59				
Repeatability	0.8					
Reproducibility	0.7					
Interaction	0.9					
R&R	1.4					
Error Tolerance	4.78					

Difference between pavement sensor and IR Thermometer from 2.5"

Repeatability

	Tech 1	Tech 2	Tech 3
R1	2.80	1.76	2.20
	2.50	1.76	2.22
	2.70	1.98	2.52
	2.32	1.78	2.54
	2.32	1.68	2.54
	2.42	1.78	2.56
	2.42	1.60	2.46
	2.34	1.70	2.28
	2.52	2.08	2.58
	2.54	2.08	2.40
R2	2.04	2.22	2.42
	2.34	2.42	2.14
	2.34	2.52	2.14
	1.94	2.24	2.34
	2.04	3.24	2.16
	2.04	2.42	2.26
	2.14	2.34	2.28
	2.34	2.44	2.30
	2.04	2.44	2.20
	2.24	2.44	2.12
StDev1	0.16	0.17	0.15
StDev2	0.15	0.29	0.10
Average	0.16	0.23	0.12
Repeatability	0.83	1.20	0.65
Error Tolerance	2.77	4.00	2.18

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.024	1	0.02	0.76	0.39	4.02
Columns	0.434	2	0.22	6.83	0.00	3.17
Interaction	2.861	2	1.43	45.04	0.00	3.17
Within	1.715	54	0.03			
Total	5.034	59				
Repeatability	0.9					
Reproducibility	0.0					
Interaction	1.9					
R&R	2.1					
Error Tolerance	7.11					

Difference between pavement sensor and IR Thermometer from 2.5" after Calibration
Repeatability

	Tech 1	Tech 2	Tech 3
R1	0.70	0.62	0.35
	0.41	0.62	0.36
	0.60	0.83	0.65
	0.23	0.64	0.66
	0.23	0.54	0.66
	0.33	0.64	0.67
	0.33	0.46	0.57
	0.24	0.55	0.39
	0.42	0.93	0.68
	0.43	0.93	0.50
R2	0.51	0.27	0.07
	0.23	0.47	0.20
	0.23	0.56	0.20
	0.60	0.29	0.01
	0.51	1.24	0.19
	0.51	0.47	0.10
	0.42	0.38	0.09
	0.23	0.47	0.08
	0.51	0.47	0.18
	0.32	0.47	0.26
StDev1	0.16	0.16	0.14
StDev2	0.14	0.27	0.08
Average	0.15	0.22	0.11
Repeatability	0.80	1.15	0.56
Error Tolerance	2.65	3.83	1.88

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.538	1	0.54	19.04	0.00	4.02
Columns	0.674	2	0.34	11.93	0.00	3.17
Interaction	0.452	2	0.23	8.00	0.00	3.17
Within	1.526	54	0.03			
Total	3.190	59				
Repeatability	0.9					
Reproducibility	0.4					
Interaction	0.7					
R&R	1.2					
Error Tolerance	3.97					

Ice Bath Field Tests

	Pavement Sensor	Thermistor	Convergence Index (Pavement Sensor)	Convergence Index (Thermistor)	Error
Tech 1	43.70	34.27			
	40.64	33.84	0.26	0.19	
	38.66	33.26	0.43	0.44	
	37.22	32.83	0.55	0.63	
	36.14	32.77	0.65	0.66	
	35.60	32.70	0.69	0.69	
	35.06	32.45	0.74	0.80	
	34.70	32.40	0.77	0.83	
	34.34	32.29	0.80	0.87	
	34.16	32.23	0.82	0.90	1.93
	33.98	32.22	0.83	0.90	
	33.62	32.20	0.86	0.91	
	33.62	32.20	0.86	0.91	
	33.62	32.16	0.86	0.93	
	33.44	32.14	0.88	0.94	
	33.26	32.14	0.89	0.94	
	33.08	32.13	0.91	0.94	
	33.08	32.13	0.91	0.94	
	33.62	32.77	0.86	0.66	
	33.44	32.29	0.88	0.87	
	33.44	32.13	0.88	0.94	
	33.08	32.09	0.91	0.96	
	33.08	32.11	0.91	0.95	
	32.90	32.09	0.92	0.96	
	32.90	32.09	0.92	0.96	
	32.90	32.09	0.92	0.96	
	32.72	32.09	0.94	0.96	
	32.72	32.09	0.94	0.96	
	32.72	32.09	0.94	0.96	
	32.72	32.07	0.94	0.97	
Tech 2		45.59			
		43.90		0.12	
		34.07		0.85	
		34.83		0.79	
		33.73		0.87	
	37.22	34.02		0.85	
	37.58	32.72	-0.07	0.95	4.86
	35.42	32.32	0.34	0.98	
	34.88	32.99	0.45	0.93	
	35.06	32.25	0.41	0.98	
	34.34	32.20	0.55	0.99	

	35.24	34.12	0.38	0.84	
	33.98	32.27	0.62	0.98	
	33.62	32.20	0.69	0.99	
	33.44	32.18	0.72	0.99	
	33.26	32.11	0.76	0.99	
	33.26	32.00	0.76	1.00	
	33.26	32.07	0.76	0.99	
	33.44	32.23	0.72	0.98	
	33.26	32.02	0.76	1.00	
	33.08	32.02	0.79	1.00	
Tech 3	58.10	36.77			
	42.98	34.12	0.58	0.55	
	36.86	33.10	0.81	0.77	
	36.86	33.04	0.81	0.78	
	35.42	32.81	0.87	0.83	
	35.42	32.52	0.87	0.89	
	35.06	32.31	0.88	0.94	2.75
	34.52	32.13	0.90	0.97	
	34.52	32.11	0.90	0.98	
	34.16	32.07	0.92	0.98	
	34.16	32.07	0.92	0.98	
	33.98	32.09	0.92	0.98	
	33.80	32.07	0.93	0.98	
	33.62	32.07	0.94	0.98	
	33.44	32.09	0.94	0.98	
	33.44	32.05	0.94	0.99	
	33.44	32.13	0.94	0.97	
	33.26	32.09	0.95	0.98	
	33.08	32.07	0.96	0.98	
	33.08	32.09	0.96	0.98	

Dry Ice Field Tests

	Tech 1	Tech 2	Tech 3	x	x*x
1	2.4	4.0	7.2	0.0	0
2	-4.1	1.9	1.3	2.0	4
3	-17.4	-7.5	-13.3	4.0	16
4	-27.0	-15.2	-23.9	6.0	36
5	-33.7	-20.3	-31.2	8.0	64
6	-38.5	-23.6	-36.0	10.0	100
7	-42.2	-26.2	-39.5	12.0	144
8	-35.7	-28.3	-42.1	14.0	196
9	-27.5	-30.0	-44.2	16.0	256
10	-21.3	-31.7	-45.8	18.0	324
11	-16.6	-33.2	-46.8	20.0	400
12	-12.8				

Linear Regression
Tech 1

SUMMARY OUTPUT				
Regression Statistics				
Multiple R	0.995608			
R Square	0.991236			
Adjusted R Square	0.986854			
Standard Error	1.97101			
Observations	7			
ANOVA				
	df	*SS*	*MS*	*F*
Regression	2	1757.535	878.7674	226.2019
Residual	4	15.53952	3.884881	
Total	6	1773.074		
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	4.233333	1.720439	2.460613	0.069646
X Variable 1	-6.13393	0.671509	-9.13455	0.000797
X Variable 2	0.185417	0.053764	3.448733	0.026085

Tech 2

SUMMARY OUTPUT				
Regression Statistics				
Multiple R	0.993685			
R Square	0.98741			
Adjusted R Square	0.984263			
Standard Error	1.663074			
Observations	11			
ANOVA				
	df	*SS*	*MS*	*F*
Regression	2	1735.373	867.6867	313.7182
Residual	8	22.12653	2.765816	
Total	10	1757.5		
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	5.868531	1.267018	4.631768	0.001684
X Variable 1	-3.8683	0.294746	-13.1242	1.08E-06
X Variable 2	0.09796	0.014194	6.901483	0.000124

Tech 3

SUMMARY OUTPUT				
Regression Statistics				
Multiple R	0.99539			
R Square	0.990802			
Adjusted R Square	0.988502			
Standard Error	2.052744			
Observations	11			
ANOVA				
	df	*SS*	*MS*	*F*
Regression	2	3631.132	1815.566	430.866
Residual	8	33.71008	4.21376	
Total	10	3664.842		
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	8.802797	1.563889	5.628786	0.000493
X Variable 1	-6.13942	0.363807	-16.8755	1.54E-07
X Variable 2	0.171562	0.01752	9.792403	9.93E-06

3. PA-Sensor D

Ambient Temperature Field Tests

Standard Deviation of 10 Stable Data Points

Name	Run	Pavement Sensor Reading	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
Tech 1	1	0.1	0.05	0.05	0.58	0.66	0.17	0.18
Tech 1	2	0.1	0.10	0.07	0.14	0.16	0.21	0.13
Tech 2	1	0.1	0.06	0.05	0.27	0.10	0.15	0.20
Tech 2	2	0.0	0.02	0.03	0.30	0.28	0.11	0.09
average		**0.1**	**0.06**	**0.05**	**0.32**	**0.30**	**0.16**	**0.15**

Note:
Temperature variation from pavement sensor is within 0.1 F so that it cannot tell the difference.

Error: Measurements from Testing Methods are Reference or Target or baseline;
Average of 10 stable points

Name	Run	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
Tech 1	1	0.53	0.64	3.49	3.73	2.07	1.93
Tech 1	2	0.54	0.89	2.09	1.91	1.69	1.72
Tech 2	1	0.64	0.66	1.04	1.39	2.07	1.71
Tech 2	2	0.59	0.76	0.26	0.43	2.26	2.11
Average		**0.58**	**0.74**	**1.72**	**1.87**	**2.02**	**1.87**

Difference between pavement sensor and Thermistor on sensor
Repeatability

	Tech 1	Tech 3
R1	0.50	0.55
	0.50	0.64
	0.50	0.64
	0.50	0.63
	0.50	0.70
	0.40	0.68
	0.60	0.67
	0.60	0.65
	0.60	0.62
	0.60	0.58
R2	0.50	0.60
	0.50	0.62
	0.50	0.62
	0.50	0.59
	0.60	0.59
	0.50	0.58
	0.60	0.59
	0.60	0.59
	0.60	0.58
	0.50	0.58
StDev1	0.07	0.05
StDev2	0.05	0.02
Average	0.06	0.03
Repeatability	0.32	0.16
Error Tolerance	1.05	0.53

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.003	1	0.00	1.08	0.31	4.11
Columns	0.064	1	0.06	27.02	0.00	4.11
Interaction	0.007	1	0.01	2.85	0.10	4.11
Within	0.085	36	0.00			
Total	0.159	39				
Repeatability	0.3					
Reproducibility	0.3					
Interaction	0.0					
R&R	0.4					
Error Tolerance	1.24					

Difference between pavement sensor and Thermistor from 2.5"

Repeatability

	Tech 1	Tech 3
R1	0.60	0.58
	0.60	0.67
	0.60	0.67
	0.60	0.60
	0.60	0.73
	0.60	0.72
	0.70	0.71
	0.70	0.68
	0.70	0.65
	0.70	0.62
R2	0.70	0.81
	0.80	0.80
	0.90	0.79
	0.90	0.77
	0.90	0.76
	0.90	0.75
	1.00	0.74
	1.00	0.75
	0.90	0.74
	0.90	0.73
StDev1	0.05	0.05
StDev2	0.09	0.03
Average	0.07	0.04
Repeatability	0.37	0.21
Error Tolerance	1.23	0.69

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.308	1	0.31	90.11	0.00	4.11
Columns	0.027	1	0.03	7.76	0.01	4.11
Interaction	0.056	1	0.06	16.24	0.00	4.11
Within	0.123	36	0.00			
Total	0.513	39				
Repeatability	0.3					
Reproducibility	0.0					
Interaction	0.4					
R&R	0.5					
Error Tolerance	1.59					

Difference between pavement sensor and IR reading
Repeatability

	Tech 1	Tech 3
R1	2.60	1.30
	2.40	1.50
	3.10	1.20
	3.60	1.20
	3.80	1.20
	3.80	0.50
	3.70	0.60
	3.90	0.90
	3.60	0.90
	3.50	1.10
R2	2.40	0.50
	2.40	0.30
	2.30	0.10
	2.20	0.10
	2.20	0.20
	1.90	0.10
	1.90	0.10
	1.70	0.30
	1.90	0.40
	2.00	0.50
StDev1	0.52	0.31
StDev2	0.24	0.16
Average	0.38	0.24
Repeatability	2.03	1.27
Error Tolerance	6.77	4.22

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	10.92	1	10.92	95.03	0.00	4.11
Columns	43.89	1	43.89	381.93	0.00	4.11
Interaction	0.70	1	0.70	6.11	0.02	4.11
Within	4.14	36	0.11			
Total	59.65	39				
Repeatability	1.7					
Reproducibility	7.6					
Interaction	1.2					
R&R	7.9					
Error Tolerance	26.22					

Difference between pavement sensor and IR reading from 2.5"
Repeatability

	Tech 1	Tech 3
R1	2.60	1.40
	2.60	1.50
	3.20	1.40
	3.80	1.40
	4.20	1.30
	4.30	1.30
	3.90	1.30
	4.00	1.30
	3.90	1.50
	3.70	1.50
R2	2.20	0.00
	2.30	0.10
	2.30	0.30
	1.90	0.30
	1.90	0.30
	1.80	0.40
	1.70	0.60
	1.60	0.70
	1.70	0.80
	1.70	0.80
StDev1	0.61	0.09
StDev2	0.26	0.28
Average	0.44	0.19
Repeatability	2.33	0.98
Error Tolerance	7.75	3.27

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	17.82	1	17.82	133.25	0.00	4.11
Columns	34.41	1	34.41	257.27	0.00	4.11
Interaction	1.41	1	1.41	10.51	0.00	4.11
Within	4.81	36	0.13			
Total	58.45	39				
Repeatability	1.9					
Reproducibility	6.6					
Interaction	1.8					
R&R	7.1					
Error Tolerance	23.73					

Difference between pavement sensor and IR Thermometer
Repeatability

	Tech 1	Tech 3
R1	2.60	1.40
	2.60	1.50
	3.20	1.40
	3.80	1.40
	4.20	1.30
	4.30	1.30
	3.90	1.30
	4.00	1.30
	3.90	1.50
	3.70	1.50
R2	2.20	0.00
	2.30	0.10
	2.30	0.30
	1.90	0.30
	1.90	0.30
	1.80	0.40
	1.70	0.60
	1.60	0.70
	1.70	0.80
	1.70	0.80
StDev1	0.11	0.15
StDev2	0.14	0.11
Average	0.13	0.13
Repeatability	0.66	0.68
Error Tolerance	2.21	2.27

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.100	1	0.10	6.10	0.02	4.11
Columns	0.784	1	0.78	47.84	0.00	4.11
Interaction	0.841	1	0.84	51.32	0.00	4.11
Within	0.590	36	0.02			
Total	2.315	39				
Repeatability	0.7					
Reproducibility	0.0					
Interaction	1.5					
R&R	1.6					
Error Tolerance	5.40					

Difference between pavement sensor and IR Thermometer from 2.5"

Repeatability

	Tech 1	Tech 3
R1	2.20	1.60
	2.10	1.90
	2.00	1.90
	1.90	1.70
	1.90	1.80
	1.90	1.70
	1.90	1.90
	1.90	1.70
	1.90	1.50
	1.90	1.40
R2	1.80	2.20
	1.70	2.30
	1.60	2.10
	1.70	2.10
	1.70	2.10
	1.70	2.10
	1.70	2.10
	1.80	2.10
	1.70	2.00
	1.80	2.00
StDev1	0.11	0.17
StDev2	0.06	0.09
Average	0.09	0.13
Repeatability	0.45	0.69
Error Tolerance	1.51	2.30

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.06	1	0.06	4.82	0.03	4.11
Columns	0.05	1	0.05	3.69	0.06	4.11
Interaction	1.02	1	1.02	77.12	0.00	4.11
Within	0.48	36	0.01			
Total	1.62	39				
Repeatability	0.6					
Reproducibility	0.0					
Interaction	1.6					
R&R	1.7					
Error Tolerance	5.81					

4. PA-Sensor C

Ambient Temperature Field Tests

Standard Deviation of 10 Stable Data Points

Name	Run	Pavement Sensor Reading	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
Tech 1	1	0.00	0.13	0.03	0.21	0.13	0.15	0.22
Tech 1	2	0.00	0.15	0.08	1.04	0.78	0.22	0.17
Tech 2	1	0.00	0.36	0.05	0.29	0.37	0.14	0.14
Tech 2	2	0.00	0.23	0.02	0.42	0.56	0.14	0.12
Average		0.00	**0.22**	**0.05**	**0.49**	**0.46**	**0.17**	**0.16**

Note:
Temperature variation from pavement sensor is within 1 F so that it cannot tell the difference.

Error: Measurements from Testing Methods are Reference or Target or baseline;
Average of 10 stable points

Name	Run	Thermistor Reading (on sensor)	Thermistor Reading (2.5" from sensor)	IR Reading OS-951 (on sensor)	IR Reading OS-951 (2.5" from sensor)	IR Thermometer OS-530HR (On Sensor)	IR Thermometer OS-530HR 2.5" from sensor
Tech 1	1	3.50	0.71	1.75	1.93	5.77	3.01
Tech 1	2	4.02	1.48	2.15	1.52	6.65	3.91
Tech 2	1	8.62	3.65	6.37	0.63	10.85	6.75
Tech 2	2	5.67	2.56	3.43	1.59	9.21	5.59
Average		**5.45**	**2.10**	**3.43**	**1.42**	**8.12**	**4.82**

Difference between pavement sensor and Thermistor on sensor
Repeatability

	Tech 1	Tech 3
R1	3.70	9.20
	3.70	9.00
	3.60	8.90
	3.50	8.80
	3.50	8.70
	3.50	8.60
	3.40	8.40
	3.40	8.30
	3.40	8.20
	3.30	8.10
R2	4.30	6.07
	4.20	5.93
	4.10	5.86
	4.10	5.76
	4.00	5.68
	4.00	5.61
	3.90	5.54
	3.90	5.46
	3.90	5.42
	3.80	5.37
StDev1	0.13	0.36
StDev2	0.15	0.23
Average	0.14	0.30
Repeatability	0.76	1.58
Error Tolerance	2.54	5.27

Repeatability and Reproducibility

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	14.76	1	14.76	257.86	0.00	4.11
Columns	114.58	1	114.58	2001.44	0.00	4.11
Interaction	30.10	1	30.10	525.80	0.00	4.11
Within	2.06	36	0.06			
Total	161.51	39				
Repeatability	1.2					
Reproducibility	10.6					
Interaction	8.9					
R&R	13.9					
Error Tolerance	46.34					

Ice Bath Field Tests

	Pavement Sensor	Thermistor	Convergence Index (Pavement Sensor)	Convergence Index (Thermistor)	Error
Tech 3	37	33.27			
	37	33.61	0.00		
	37	32.49	0.00	0.00	
	37	32.14	0.00	0.71	
	37	32.16	0.00	0.67	
	37	32.09	0.00	0.82	
	37	32.05	0.00	0.90	NR
	37	32.05	0.00	0.90	
	37	32.22	0.00	0.55	
	37	32.28	0.00	0.43	

I Surface State Tests

1. MN-Sensor A

Tech 1 Jan. 25	Local Time of Day	Visual Observation	RPU Surface Status	Water Thickness	Agree	Method	Time (min)
	13:55	Dry	Dry	Not Recorded	Y	S	0
	14:02	Wet	Dry	Not Recorded			
	14:07	Wet	Damp	Not Recorded	Y	W	10
Tech 2 Jan. 27	**Local Time of Day**	**Visual Observation**	**RPU Surface Status**	**Water Thickness**			
	11:21	Dry	Dry	Not Recorded	Y	S	0
	11:28	Wet	Damp	0.5 mm	Y	W	7
	11:47	Frozen	Watch	0.5 mm	Y	W	26
Tech 3 Jan. 28	**Local Time of Day**	**Visual Observation**	**RPU Surface Status**	**Water Thickness**			
	11:03	Dry	Dry	Not Recorded	Y	S	0
	11:09	Wet	Not Recorded	< 1 mm			
	11:10	Frozen	Not Recorded	1 mm			
	11:28	Wet	Not Recorded	Full well			

2. NV-Sensor B

Tech 1

Feb. 23 Tech 1	Local Time of Day	Visual Observation	Pavement Surface State Code, item 36	Surface Status	Water Thickness, item 42	Concentration g/l. item 39	Agree	Method	Time (min)
	9:50	dry	21	Cloudy Dry	0.00	0.0	Y	S	0
Applied Tap Water									
	9:52	wet	31	Clear Dry	0.00	0.0			
	9:54	wet	32	Clear Moist	0.00	0.0	Y	W	4
Dried sensor surface with paper towel									
	9:56	dry	32	Clear Moist	0.00	0.0			
	9:58	dry	32	Clear Moist	0.00	0.0			
	10:00	dry	31	Clear Dry	0.00	0.0	Y	P	6
	10:02	dry	31	Clear Dry	0.00	0.0	Y	P	6
	10:04	dry	21	Cloudy Dry	0.00	0.0			
Applied Tap Water									
	10:06	wet	31	Clear Dry	0.00	0.0			
	10:08	wet	32	Clear Moist	0.00	0.0	Y	W	4
	10:10	wet	32	Clear Moist	0.00	0.0	Y	W	4
	10:12	wet	33	Clear Wet	0.03	0.0			
					0.13				

Tech 2

Feb. 24 Tech 2	Local Time of Day	Visual Observation	Pavement Surface State Code, Item 36	Surface Status	Water Thickness, item 42	Concentration g/l. item 39			
	9:26	dry	31	Clear Dry	0.00	0.0	Y	S	0
Added tap water-soaked paper towel									
	9:28	wet	31	Clear Dry	0.00	0.0			
	9:30	wet	33	Clear Wet	0.07	0.0	Y	WP	4
	9:32	wet	33	Clear Wet	0.14	0.0	Y	WP	4
	9:34	wet	33	Clear Wet	0.23	0.0			
Dried sensor surface with paper towel									
	9:36	dry	33	Clear Wet	0.32	0.0			
Dried sensor surface with paper towel again									
	9:38	dry	33	Clear Wet	0.40	0.0			
	9:40	dry	33	Clear Wet	0.42	0.0			
	9:42	dry	33	Clear Wet	0.41	0.0			
	9:44	dry	33	Clear Wet	0.36	0.0			
	9:46	dry	33	Clear Wet	0.29	0.0			
	9:48	dry	32	Clear Moist	0.23	0.0			
	9:50	dry	22	Cloudy Moist	0.17	0.0			
	9:52	dry	22	Cloudy Moist	0.13	0.0	N	2P	18
	9:54	dry	32	Clear Moist	0.10	0.0	N	2P	20
Dried sensor surface with heat gun									
	9:56	dry	32	Clear Moist	0.08	0.0			
	9:58	dry	32	Clear Moist	0.06	0.0			
Dried sensor surface with heat gun again									
	10:00	dry	31	Clear Dry	0.05	0.0	Y	2H	6
	10:02	dry	31	Clear Dry	0.04	0.0	Y	2H	6
	10:04	wet	31	Clear Dry	0.03	0.0			
Added tap water-soaked paper towel									
	10:06	wet	32	Clear Moist	0.02	0.0	Y	WP	2
	10:08	wet	33	Clear Wet	0.08	0.0	Y	WP	2

Tech 3

Feb. 25 Tech 3	Local Time of Day	Visual Observation	Pavement Surface State Code, item 36	Surface Status	Water Thickness, item 42	Concentration g/l. item 39	Agree	Method	Time (min)
	9:37	dry	31	Clear Dry	0.00	0.0			
	9:39	dry	31	Clear Dry	0.00	0.0	Y	S	0
	9:41	dry	31	Clear Dry	0.00	0.0	Y	S	0
Added tap water-soaked paper towel									
	9:43	wet	31	Clear Dry	0.00	0.0			
	9:45	wet	32	Clear Moist	0.07	0.0	Y	WP	4
	9:47	wet	33	Clear Wet	0.16	0.0	Y	WP	4
	9:49	wet	33	Clear Wet	0.26	0.0			
Dried sensor surface with paper towel									
	9:51	dry	33	Clear Wet	0.35	0.0			
	9:53	dry	33	Clear Wet	0.37	0.0			
	9:55	dry	33	Clear Wet	0.35	0.0			
	9:57	dry	33	Clear Wet	0.28	0.0			
	9:59	dry	33	Clear Wet	0.22	0.0			
	10:01	dry	32	Clear Moist	0.17	0.0			
	10:03	dry	32	Clear Moist	0.13	0.0			
	10:05	dry	32	Clear Moist	0.10	0.0			
	10:07	dry	32	Clear Moist	0.08	0.0	N	P	16
	10:09	dry	32	Clear Moist	0.06	0.0	N	P	16
Dried sensor surface with heat gun									
	10:11	dry	32	Clear Moist	0.04	0.0			
	10:13	dry	31	Clear Dry	0.03	0.0	Y	H	4
	10:15	dry	31	Clear Dry	0.03	0.0	Y	H	4
Added tap water-soaked paper towel									
	10:17	wet	31	Clear Dry	0.02	0.0			
	10:19	wet	32	Clear Moist	0.08	0.0	Y	WP	4
	10:21	wet	33	Clear Wet	0.17	0.0	Y	WP	4
	10:23	wet	33	Clear Wet	0.29	0.0			

3. PA-Sensor D

Tech 3	23-Mar-05				
Local Time of Day	**Visual Observation**	**Pavement Surface State (from RPU)**	**Agree**	**Method**	**Time (min)**
1:00	dry	dry	Y	S	0
Applied tap water to sensor surface					
1:05	wet	wet	Y	W	5
1:17	wet	wet	Y	W	5
Dried sensor surface with heat gun					
1:24	dry	dry	Y	H	7
Applied tap water to sensor surface					
1:26	wet	wet	Y	W	2
1:27	wet	wet	Y	W	2
Dried sensor surface with heat gun					
1:29	dry	dry	Y	H	2
1:31	dry	dry	Y	H	2
Applied tap water to sensor surface					
1:35	wet	wet	Y	W	4
1:37	dry	dry	Y	H	2

4. PA-Sensor C

Tech 1

Tech 1 3/22	Local Time of Day	Visual Observation	Surface Status	Chemical Index	Agree	Method	Time (min)
	11:02	dry	dry	0	Y	S	0
	11:04	wet	dry	0			
Applied tap water to sensor surface							
	11:06	wet	chemically wet	32	Y	W	4
	11:08	wet	chemically wet	32	Y	W	4
Dried sensor surface with heat gun							
	11:16	dry	dry	0	Y	H	8
	11:18	dry	dry	0	Y	H	8
	11:20	wet	dry	0			
Applied tap water to sensor surface							
	11:22	wet	chemically wet	22	Y	W	4
	11:24	wet	chemically wet	25	Y	W	4
Dried sensor surface with heat gun							
	11:26	dry	chemically wet	26			
	11:28	dry	dry	0	Y	H	4
	11:30	dry	dry	0	Y	H	4
Applied tap water to sensor surface							
	11:32	wet	dry	0			
	11:34	wet	chemically wet	32	Y	W	4
	11:36	wet	chemically wet	33	Y	W	4
	11:38	wet	chemically wet	32			
	11:40	wet	chemically wet	32			
	11:42	dry	chemically wet	31			
Dried sensor surface with heat gun							
	11:44	dry	dry	0	Y	H	4

Tech 3

Tech 3 3/22	Local Time of Day	Visual Observation	Surface Status	Chemical Index	Agree	Method	Time (min)
	11:51	dry	dry	0	Y	S	0
Applied tap water to sensor surface							
	11:55	wet	wet	48	Y	W	4
	11:57	wet	wet	52	Y	W	4
Dried sensor surface with heat gun							
	11:59	dry	dry	0	Y	H	2
	12:01	dry	dry	0	Y	H	2
Applied tap water to sensor surface							
	12:03	wet	wet	24	Y	W	2
	12:05	wet	wet	26	Y	W	2
Dried sensor surface with heat gun							
	12:07	dry	dry	0	Y	H	2
Applied tap water to sensor surface							
	12:09	wet	wet	36	Y	W	2
	12:11	wet	wet	37	Y	W	2

II Freezing Point Tests

1. MN-Sensor A (passive)

Standard Deviation of 3 Data Points

Name	Run	4%	10%	15%	Saturated
Tech 1	1	0.01	0.05	0.09	0.36
Tech 1	2	0.02	0.07	0.14	
Tech 2	1	0.00	0.06	0.19	0.54
Tech 3	1	0.05	0.30	0.06	
Average		**0.02**	**0.12**	**0.12**	**0.45**

Error: Baseline is theoretical; Average of 3 data points

Name	Run	4%	10%	15%	Saturated
Baseline		27.7	20.2	12.4	-5.2
Tech 1	1	0.33	1.34	3.66	13.28
Tech 1	2	0.31	1.17	3.19	
Tech 2	1	0.30	1.29	3.29	13.02
Tech 3	1	0.34	1.50	3.65	
Average		**0.31**	**1.26**	**3.38**	**13.15**

4% Repeatability

4%	R1	R2
Reading	Freezing Point (F)	Freezing Point (F)
1	28.02	27.99
2	28.03	28.02
3	28.04	28.03
StDev1	0.01	
StDev2	0.02	
Average	0.02	
Repeatability	0.09	
Error Tolerance	0.30	

4% ANOVA Significance

4%	A	B	C	D
Reading	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)
1	28.02	27.99	28.02	27.99
2	28.03	28.02	28.03	28.02
3	28.04	28.03	28.04	28.03

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.003233	3	0.001078	1.558233	0.27343	4.06618
Within Groups	0.005533	8	0.000692			
Total	0.008767	11				
Accept						

10% Repeatability

10%	R1	R2
Reading	Freezing Point (F)	Freezing Point (F)
1	21.49	21.29
2	21.59	21.43
3	21.53	21.39
StDev1	0.08	
StDev2	0.11	
Average	0.09	
Repeatability	0.51	
Error Tolerance	1.71	

10% ANOVA Significance

10%	A	B	C	D
Reading	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)
1	21.41	21.19	21.54	21.36
2	21.49	21.29	21.55	21.85
3	21.59	21.43	21.44	21.89

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.236292	3	0.078764	2.776635	0.11031	4.06618
Within Groups	0.226933	8	0.028367			
Total	0.463225	11				
Accept						

15% Repeatability

15%	R1	R2
Reading	Freezing Point (F)	Freezing Point (F)
1	15.92	15.68
2	16.17	15.45
3	16.02	15.72
4	16.00	15.60
StDev1	0.10	
StDev2	0.12	
Average	0.11	
Repeatability	0.63	
Error Tolerance	2.08	

15% ANOVA Significance

15%	A	B	C	D
Reading	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)	Freezing Point (F)
1	15.92	15.68	15.51	15.73
2	16.17	15.45	15.57	16.10
3	16.02	15.72	15.59	16.05
4	16.00	15.60	15.90	15.99

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.5566	3	0.185533	8.959356	0.002174	3.4903
Within Groups	0.2485	12	0.020708			
Total	0.8051	15				
Accept at 0.01 Reject at 0.05						

Saturated ANOVA Significance

4%	A	B
Reading	Freezing Point (F)	Freezing Point (F)
1	7.43	6.62
2	8.08	8.13
3	7.72	8.13
4	8.44	7.20

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.316013	1	0.316013	0.849239	0.392315	5.987374
Within Groups	2.232675	6	0.372112			
Total	2.548688	7				
Accept						

2. NV-Sensor B (passive)

Standard Deviation of 10 Stable Data Points

Name	Run	1%	4%	10%	15%
Tech 1	1		0.27	0.69	1.41
Tech 1	2		1.60	0.40	
Tech 2	1	0.67	0.54	7.75	
Tech 2	2	0.45	0.37		
Tech 3	1	0.15	0.23	2.58	
Tech 3	2	0.18	0.85		
Average		**0.36**	**0.64**	**2.85**	**1.41**

Error: Baseline is theoretical; Average of 10 data points

Name	Run	1%	4%	10%	15%
Baseline		30.94	27.68	20.12	20.12
Tech 1	1		1.94	6.01	7.70
Tech 1	2		4.34	7.87	
Tech 2	1	0.18	8.17	18.20	
Tech 2	2	5.54	0.23		
Tech 3	1	1.33	2.77	5.80	
Tech 3	2	1.62	1.91		
Average		**2.17**	**3.23**	**9.47**	**7.70**

Accuracy Recommendation:

Since we use the absolute difference to analyze errors we note only deviations in one direction and ignore deviations in the other direction. Therefore, the one-tailed method is appropriate to establish the confidence limits. To find a one-tailed limit with confidence probability of 95% we want a normal deviate Z such that the area beyond Z in one tail is 0.05. In a noraml distribution table the area from 0 to Z will be 0.45, and the value of Z is 1.645. A part from 5% chance in drawing the sample with the size of n:

average + 1.645 standard deviation / square root of n

To choose a fail/pass criteria we have three parameters to specify: average, standard deviation, and size of a sample. In error analysis, 1.32F is the accuracy and 0.7F is the precision. Since the distribution of random errors follows the normal distribution with zero average and standard deviation from Gauss 1.32F indicates a systematic error and 0.7F is the random error.

If we assume the test will follow the same distribution (average and standard deviation) we can choose the number of samples to draw for the future test:

3.23+1.645 x .31 / 2 = 3.5 F

1% Repeatability

	Tech 2	Tech 3
R1	30.56	29.84
	30.38	29.84
	30.20	29.66
	30.02	29.66
	29.84	29.66
	30.74	29.48
	31.10	29.48
	31.46	29.48
	31.64	29.48
	31.64	29.48
R2	26.42	29.48
	25.88	29.30
	25.52	29.30
	25.34	29.12
	25.16	29.12
	24.98	29.12
	24.98	29.30
	25.16	29.30
	25.16	29.48
	25.34	29.66
StDev1	0.67	0.15
StDev2	0.45	0.18
Average	0.56	0.16
Repeatability	2.96	0.87
Error Tolerance	9.88	2.89

1% ANOVA Significance

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	79.86276	1	79.86276	452.7367	5.58E-22	4.113161
Columns	19.20996	1	19.20996	108.9	1.96E-12	4.113161
Interaction	64.41444	1	64.41444	365.1612	1.97E-20	4.113161
Within	6.3504	36	0.1764			
Total	169.8376	39				
Reject						

4% Repeatability

	Tech 1	Tech 2	Tech 3
R1	29.12	20.66	30.74
	29.84	20.12	30.92
	29.84	19.76	30.56
	29.84	19.58	30.20
	29.84	19.40	30.20
	29.84	19.22	30.38
	29.66	19.22	30.38
	29.48	19.04	30.38
	29.48	19.04	30.38
	29.30	19.04	30.38
R2	26.24	27.14	28.76
	25.34	27.50	28.40
	24.62	27.68	28.04
	23.72	27.86	29.66
	23.18	28.04	30.02
	22.64	28.04	30.20
	22.28	28.22	30.20
	21.92	28.22	30.20
	21.74	28.22	30.20
	21.74	28.22	30.20
StDev1	0.27	0.54	0.23
StDev2	1.60	0.37	0.85
Average	0.93	0.45	0.54
Repeatability	4.93	2.40	2.86
Error Tolerance	16.44	8.02	9.54

4% ANOVA Significance

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	2.646	1	2.646	4.145516	0.046663	4.01954
Columns	399.9856	2	199.9928	313.3308	1.93E-30	3.168246
Interaction	551.7083	2	275.8541	432.1836	5.93E-34	3.168246
Within	34.46712	54	0.63828			
Total	988.807	59				
Reject						

10% Repeatability

	Tech 1
R1	15.44
	14.90
	14.54
	14.36
	14.00
	13.82
	13.64
	13.64
	13.46
	13.28
R2	11.30
	11.84
	12.20
	12.38
	12.38
	12.56
	12.56
	12.56
	12.38
	12.38
StDev1	0.69
StDev2	0.40
Average	0.54
Repeatability	2.88
Error Tolerance	9.61

10% ANOVA Significance

S2	Tech 2	Tech 3
11.30	14.18	29.30
11.84	11.66	29.30
12.20	8.78	27.50
12.38	5.54	27.50
12.38	2.30	26.60
12.56	-0.94	25.70
12.56	-4.36	24.98
12.56	-5.98	23.36
12.38	-5.98	22.46
12.38	-5.98	22.46

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2897.042	2	1448.521	65.02164	4.75E-11	3.354131
Within Groups	601.493	27	22.27752			
Total	3498.535	29				
Reject						

3. PA-Sensor D (active)

Standard Deviation of Variable Data Points

Name	**Run**	**10%**
Tech 1	1	0.14
Tech 2	1	0.00
Average		**0.07**

Error: Measurements from Testing Methods are Reference or Target or baseline; Average of variable data points.

Name	**Run**	**10%**
Baseline		20.2
Tech 1	1	1.90
Tech 2	1	2.90
Average		**2.40**

10% ANOVA Significance

	Tech 1	Tech 3
R1	22.20	23.10
R2	22.00	23.10

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	0.01	1	0.01	1	0.5	161.4462
Columns	1	1	1	100	0.063451	161.4462
Error	0.01	1	0.01			
Total	1.02	3				
Accept						

PART II: FIELD TEST PROCEDURES FOR TESTING ENVIRONMENTAL SENSOR STATIONS

TABLE OF CONTENTS FOR PART II

COMMON TERMS

Central Server: Computer that collects data from many ESS sites

ESS (Environmental Sensor Station): All the components of a roadside weather station including atmospheric and pavement sensors

RPU (Remote Processing Unit): Electronic device that communicates with sensors, located roadside at the ESS site

RWIS (Road Weather Information System): Entire system for monitoring road weather over a usually large geographic region

PARTICIPATING VENDORS

Special thanks to the following vendors for their participation in the field test portion of this project.

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Nu-Metrics, Inc.
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Uniontown, PA 15401
Tel. (800) 346-2025

Surface Systems, Inc.
11612 Lilburn Park Road
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Tel. (314) 569-1002

Vaisala Inc.
PO Box 3659
Boulder, CO 80307
Tel. (303) 499-1701

1. INTRODUCTION

At least 42 state departments of transportation (DOTs) and other public and private sector agencies which use Road Weather Information Systems (RWIS) typically specify requirements for the accuracy of instruments at Environmental Sensor Stations (ESS) at the time of procurement. These instruments include atmospheric and pavement surface and subsurface sensors. Most agencies rely on vendor-developed testing and calibration methods or they accept the sensor data without regular testing of calibration. This creates uncertainty in the accuracy of the data generated by the sensors and compromises the value of the information in decision-making.

As part of the National Cooperative Highway Research Program (NCHRP) it was determined that a need existed to develop guidelines for practical field testing of ESS sensors to evaluate if a sensor is providing an accurate representation of actual conditions at the installed site.

The procedures contained in this document define the equipment and describe the procedures that state, county and city personnel can use to measure sensor parameters and evaluate sensors.

The standardized methodologies for field testing various models of ESS *pavement* sensors were developed as a result of research performed by SRF Consulting Group, Inc., Braun Intertec and International Idea Institute, Inc. under NCHRP Project 6-15, Testing and Calibration Methods for RWIS Sensors. Pavement temperature, surface state, and freezing point temperature are the three pavement sensor parameters that were addressed in the study.

In order to develop these procedures, extensive laboratory and field tests were conducted, analyzed and documented. The basic approach of the process was a comparative test between baseline and pavement sensor data. Various potential field test procedures were developed and evaluated using a laboratory environment where external variables could be controlled and the tests could be repeatedly run. Based on these tests, a draft document of standard field test procedures was prepared. These draft field test procedures were then evaluated during on-site field testing in Minnesota, Nevada and Pennsylvania before being finalized for this document.

2. TEST PREPARATION

2.1 PERSONNEL TRAINING

The first step in preparing for field testing is to adequately train the personnel that will be responsible for field test activities. A trained presenter, using a PowerPoint presentation (available at http://trb.org/news/blurb_detail.asp?id=6163) that was developed to complement these guidelines, usually provides training for these test procedures. During the training presentation, all the testing equipment should be on hand so that the presenter can illustrate the procedures effectively. After the training, both the presenter and trainees should run through the test procedures together. They should read each test procedure and perform each step either at a simulated test area, such as a parking lot, or gathered around a table. This hands-on experience is essential for learning and understanding the tests.

Also, test equipment will need to be procured and prepared. Lists of that equipment can be found in the Field Test Procedures Section.

Figure 1. Classroom Training.

3. SAFETY CONSIDERATIONS

In order to do accurate field testing of pavement sensors, physical contact with the sensors is required. This means that personnel will be working on the roadway in a lane closure. Some necessary safety precautions **must** be taken to ensure the safety of both test operators and drivers on the highway.

3.1. PERSONNEL SAFETY

Safety is always a critical issue when working on highways, but it becomes increasingly important when the test operator is subjected to long hours near very fast-moving traffic. Because of this consideration, safety must be taken as the first priority when running the tests.

- If traffic, weather or any other conditions develop while running the tests that create safety hazards, testing should be halted immediately until the conditions improve or the problem can be resolved.
- Depending on factors, such as how far the operator must travel to the test site, how many tests are required and how the sensor responds, the operator may be required to work long hours or may become fatigued. Although a single person may run the procedures, an additional operator is recommended to aid and/or replace the first operator if necessary.
- Many of the tests will be conducted under poor or extreme weather conditions and most require that the sensor be shielded from solar radiation. Use of a shelter tent or collapsible ice fishing shelter, adequately anchored to the pavement, is therefore recommended to protect the operator and shield the sensor during the tests.

To provide additional operator protection it is strongly recommended that a crash truck be provided in addition to the required lane closure.

3.2. ELECTROSTATIC DISCHARGE PROTECTION

Many of these procedures require protection from electrostatic discharge (ESD). If the RPU and pavement sensor equipment is not handled properly, ESD can be hazardous to the operator and damage the equipment. In order to properly deal with electrical devices, please carefully read the equipment manuals.

3.3. LANE CLOSURES

Lane closures are required for pavement sensor testing so that the pavement sensors can be accessed directly. Because the procedures involve contact with the surface of the pavement and sensor, adequate space to safely run the procedures is necessary. Information about safe lane closures may be found in the Manual on Uniform Traffic Control Devices (MUTCD) available from the Federal Highway Administration. Because different states have different policies, it is best to check with the locally adopted MUTCD and follow any other safety considerations that may apply. Figure 3 illustrates a crash truck being used to protect a work area, in this case, the left lane of a four-lane divided roadway.

Figure 2. Operator Performing Tests in a Closed Lane.

Figure 3. Crash Truck Protecting Operators in a Lane Closure.

4. ESS DATA COLLECTION METHODS

4.1 METHODS FOR OBTAINING RPU DATA

In most pavement sensor installations, the sensor passes data to a Remote Processing Unit (RPU), usually located in a cabinet near the site of the pavement sensor. This RPU may often be accessed by a computer via a serial, modem or Ethernet connection. In order to access this data at any given field site, it will be necessary to either access the RPU's data locally with a portable computer or call a central server or office for the information. Depending on the situation, this could be performed using cell voice or data service.

Based on the findings during the research for developing these guidelines, some RPU manufacturers will not release detailed RPU access information for publication. In addition, each manufacturer has different procedures to access their RPUs. Therefore, it is necessary for the individual agency or the owner of the equipment to directly obtain the necessary RPU access procedures from the RPU manufacturer. Once the agency has access to the RPU, the procedures for testing the pavement sensor will be the same for all pavement sensors, regardless of the sensor manufacturer. The owner of the equipment should be able to obtain the information necessary to access the RPUs from the manufacturer who they have purchased the equipment from. Note that some manufacturers may require their technicians to be at the sensor site to access the RPUs. The usefulness of these test procedures depends on having access to data from the test site.

Another issue that the agency will need to resolve, through the manufacturer, is how their sensor determines surface conditions. Some sites use information inputs other than pavement sensor readings to determine a single parameter. A common issue can appear during the surface state tests. Sometimes, the wrong surface condition is displayed if the RPU requires inputs from atmospheric sensors for precipitation and humidity to determine the surface state. For example, if a sensor is dried and sheltered from precipitation on a rainy day, the sensor may not report dry because its precipitation sensor detects the rain. Knowledge of these sensor intricacies is essential to producing accurate evaluations. Sensor vendors have a good understanding of these phenomena.

Another issue to address before performing the tests is changing the interval between readings. Because all the tests to be conducted require timely information, it is best if the pavement sensor data can be read at two-minute increments. RWIS data is typically not updated or needed this often. Therefore, in order to run these tests effectively, it likely will be necessary to configure the RPU or computer to give more frequent updates.

The following sections present two methods for obtaining data from the RPU. These procedures are general enough to apply to many types of ESS stations.

4.2 ACCESSING AN RPU DIRECTLY

Most RPUs can be configured to send serial data to a computer. A terminal program running on the portable computer can often read this data if the data rates are set appropriately. Usually, this information is given in a delimited format that can be understood without decoding. For example, the data in the third column might be temperature data, while the fourth column might be a surface state in a binary format, such as "0" for "dry" and "1" for "wet." Data format information is available from the vendor.

In order to access the RPU, each state highway agency should contact the RPU manufacturer to determine the best way to access the data. The manufacturer may also have expertise that will make the testing run more efficiently.

Typical RPUs can send data to a computer over a 9-pin serial connection with an RS-232 connector. This can be connected to the computer via the COM port. This scenario is shown in Figure 4. In some cases, it may be necessary for a manufacturer's representative to be on hand to access the RPU data directly. In other cases, this person may be able to configure the sensor to make it more useful for the sensor testing.

In some cases, the RPU is connected to a serial server that may be accessed with a TCP/IP connection through a hub at the ESS site. This type of connection is advantageous because the portable computer may be connected to the ESS system without changing the way the system functions. This scenario is shown in Figure 5.

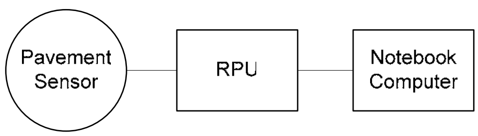


Figure 4. Possible Testing Configuration – Version A

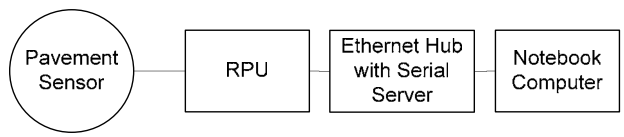


Figure 5. Possible Testing Configuration – Version B

A caveat to these approaches is that the distance from the RPU to the pavement sensor site is often too far or crosses a traffic lane. In certain cases it may be necessary to use special hardware to send serial or Ethernet data over a long distance. Possible solutions are wireless serial data radios or line drivers which send the data over twisted pair. If these solutions are not available, it may be necessary for one operator to stand at the RPU site and tell the other operator the sensor status over a radio. Obviously, this is not an optimal situation, but it removes some of the technical issues.

4.3. CALL UP CENTRAL SERVER

It will not always be possible to access the RPU by connecting a portable computer to it in the field. In those cases, it will be necessary to contact a central office or server to receive the data from the end user. Someone in the central office would then convey the data to field personnel. However, these systems may not update frequently enough to get the data required for the test procedures. If this is the case, it may be possible to configure them to update more frequently, such as every two minutes. This scenario is shown in Figure 6.

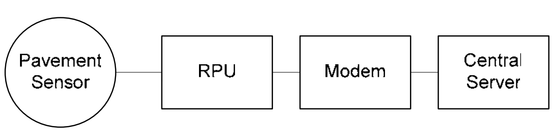


Figure 6. Possible Testing Configuration – Version C

5. FIELD TESTING PROCEDURES FOR PAVEMENT SENSORS

The following detailed procedures can be used for testing the performance of in-situ pavement sensors. This section also contains a listing of equipment and supplies for each test. The procedures described here have been developed and tested to assure they provide accurate and repeatable results.

These are testing procedures that are conducted in-situ, usually on busy highways, close to traffic. It is critical that the all safety procedures outlined in Chapter 3 be addressed and followed first before beginning any field-testing.

During the testing program it was determined that ESS Pavement Sensors were not adaptable to field calibration. Therefore no field calibration procedures are shown for ESS Pavement Sensors.

5.1 PAVEMENT SENSOR TESTING OVERVIEW

The following five different field-tests are provided for the complete testing of ESS Pavement Sensors under various conditions:

- Pavement Sensor Test 1: Pavement Temperature at Ambient Conditions
- Pavement Sensor Test 2: Pavement Surface (Dry/Wet/Ice) Conditions
- Pavement Sensor Test 3: Freezing Point of Passive and Active Pavement Sensors
  - Pavement Sensor Test 3A: Testing Freezing Point Using Passive Sensors
  - Pavement Sensor Test 3B: Testing Freezing Point Using Active Sensors
- Pavement Sensor Test 4: Ice Bath at 32º F (Optional)

It is recommended that the test be run in the order they are presented. The ambient temperature test is presented first so that it can test the undisturbed pavement and sensors. The surface state test is next because it is desirable to run that test before any salt has been introduced to the sensor surface. Salt will lower the freezing point and make it more difficult to form ice. The freezing point test may be run at any time. The optional ice bath test should be run last because it lowers the temperature and could affect the time it takes to run the other tests.

5.2 EQUIPMENT RECOMMENDED FOR TEST SETUP

As explained in Section 4, ESS Data Collection, field tests require some form of data collection. An ideal method is to be connected directly to the RPU. If the live RPU data can be seen at the sensor site, the tests can be run more quickly and effectively. Other methods are available that may not require the use of this equipment.

The following equipment is recommended:

- Portable computer and communication cables for accessing the RPU to get the pavement sensor data
- Extension cords to power the computer at the sensor site

		
Portable computer	Communication cables	Extension cords (200 feet or longer as needed)

5.3 OPTIONAL EQUIPMENT REQUIRED FOR TEST SETUP

If extension cords do not reach the pavement sensor site or AC power is not available, it may be necessary to use a power inverter and power the equipment from the operator's roadside vehicle. Communication with the RPU may be an issue, but wireless serial communications devices are available.

Fortunately, almost all commercially available power inverters are capable of powering a portable computer. However, Field Test 2 requires the use of a heat gun that requires a powerful inverter. Please make sure that the power inverter can power the heat gun before field testing. If not, a portable generator could be substituted. A propane heater is another option.

A digital camera is useful for documenting the condition of the sensor and the weather conditions during testing. It is also useful for documentation of a particular phenomenon that may happen during the testing period.

5.4 VERIFYING DATA CAPTURE

When the computer is properly connected to the RPU, or other arrangements have been made to get live data, the computer should be tested to verify that all necessary data is available and is giving reasonable values. **Record** the initial test conditions on the first page of the Testing and Maintenance Forms for Pavement Sensors found in Appendix C. Also record the observed pavement sensor condition in the Observation section of the form.

The following data is required:

- Pavement sensor temperature
- Ambient temperature
- Dew point temperature
- Surface state
- Freezing point

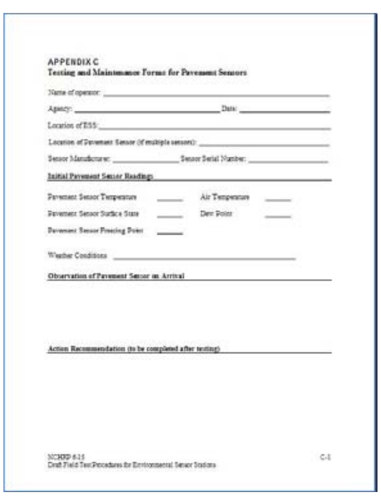
Verify that the data is showing reasonable values and record your observations in the Observation section of the form. The following suggestions may help:

- The thermometer and thermistor in Field Test 1 may be used to get relatively close ambient temperature conditions.
- The thermistor can be changed from Celsius to Fahrenheit by holding the bottom of the rocker switch for ten seconds.
- To quickly estimate a conversion from Celsius to Fahrenheit, double the Celsius temperature and add 32.
- Surface states are often coded as a number in the serial output. Refer to the manufacturer's manuals if the surface state is not evident.
- Freezing point often does not give a reading unless the pavement sensor is wet.

5.5 EQUIPMENT REQUIRED FOR ALL TESTS

The pictured test equipment is required for all tests. This equipment should be readily available during testing.

- All tests require some sort of timekeeping
- A knee pad, such as for gardening, is recommended because many of the tests require the operator to work with the pavement sensor directly.
- Paper towels are generally used for cleaning the pavement sensor. Disposable towels are recommended because the thermal paste in Field Test 1 is difficult to wash out of cloth towels.
- A supply of Testing and Maintenance Forms for Pavement Sensors should be copied from Appendix C before the testing.


APPENDIX C
Testing and Maintenance Forms for Pavement Sensors

Name of operator: ______
Agency: ______ Date: ______
Location of ESS: ______
Location of Pavement Sensor (if multiple sensors): ______
Sensor Manufacturer: ______ Sensor Serial Number: ______

Initial Pavement Sensor Readings

Pavement Sensor Temperature ____ Air Temperature ____
Pavement Sensor Surface State ____ Dew Point ____
Pavement Sensor Freezing Point ____

Weather Conditions ______

Observation of Pavement Sensor on Arrival

Action Recommendation (to be completed after testing)

NCHRP 6-15
Draft Field Test Procedures for Environmental Sensor Stations C-1

Copies of the Testing and Maintenance Forms (Appendix C)


Knee pad


Paper Towels

Calculator


Watch for keeping time

5.6 PAVEMENT SENSOR TEST 1: PAVEMENT TEMPERATURE AT AMBIENT CONDITIONS

Field Test 1 measures the pavement sensor's temperature accuracy at ambient conditions.

Test Condition Notes:

- This test may be done at any temperature where reasonable test conditions can be maintained. The test is best done around daybreak to avoid solar radiation. Be sure the sensor and thermistors are shaded from solar radiation for at least 15 minutes prior to the test and also during the test.
- Thermistors and thermometers should be calibrated regularly by a reputable calibration authority and have a current calibration certificate.
- If the test must be done after the sun has warmed the pavement sensor, the sensor must be shielded from solar radiation for an hour or more.
- The sensor surface must remain dry and clean throughout the test.
- The thermal paste becomes stiff if subjected to cold temperatures. It is best to keep the thermal paste warm until it is needed.
- The thermistor will require time to stabilize after being handled.

Equipment and Supplies Required

		
Thermal conducting Paste	Brick with insulation on bottom surface to secure thermistor to pavement sensor	Two handheld thermometers with precision thermistors
		
Supply of tap water to clean pavement	Nylon brush to clean the pins on top of the sensor	Shelter tent, such as a collapsible ice fishing shelter
		
Paint can opener		

Field Testing Procedures – Test 1: Pavement Temperature at Ambient Conditions

To test the pavement sensor for temperature accuracy at ambient conditions, perform the following steps:

Step 1 Read all the manuals and manufacturer's literature on operating the participating sensor. Also read and observe all the safety precautions in Chapter 3.

Step 2 Shield the pavement sensor from solar radiation to block the effects of the environment. Wait at least 15 minutes (or an hour for afternoon testing) for the effects of the solar radiation to dissipate before taking the first reading.

Step 3 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the portable computer.

Step 4 Clean and dry the sensor and surrounding one foot area using paper towels.

Step 5 Affix one thermistor to the pavement 2.5" from the sensor and one directly on the sensor using thermally conductive paste.

- Avoid placing the thermistor on the sensor electrodes or in the depression.
- The metallic side of the thermistor should face down.

Step 6 Place the insulated brick on the thermistor. Attach the lead wires from the thermistors to the thermometers.

Step 7 **Record** the following readings at two minute intervals on the Testing and Maintenance Forms until there have been four stable readings for both the thermistor and the pavement sensor:

- Pavement sensor temperature (from RPU)
- Thermistors on pavement sensor and pavement surface

Stability occurs when the both thermistor on pavement surface and RPU reading from pavement sensor vary less than 0.4º F (0.2º C) between four successive readings.

Step 8 Determine the average of the four stable readings for each thermistor and the pavement sensor and **record** the values on the Testing and Maintenance Forms.

Step 9 Clean the thermal paste from the surface of the pavement sensor with the paper towels and brush.

> The sensor fails this test if the average values for the pavement sensor and thermistor 2.5" from the sensor disagree by more than 2.0º F (1.1º C).
> - The thermistor 2.5" away from the sensor should be used as the main baseline.
> - The thermistor on the sensor should be used to better understand the test environment.
>
> If the sensor fails the first test, run the test an additional two times to verify the failure.

Figure 7. Applying Thermal Paste to Sensor.

Figure 8. Completed Pavement Temperature Test Setup (Only One Thermistor Required).

5.7 PAVEMENT SENSOR TEST 2: PAVEMENT SURFACE (DRY/WET/ICE) CONDITIONS

Field Test 2 includes tests for determining dry, wet and ice surface state conditions. Most RPUs determine whether the sensor is dry or not dry by measuring the conductivity of two electrodes on the sensor. Depending on the sensor, the RPU may also use temperature information to detect ice.

Test Condition Notes:

- The weather must be dry or the pavement sensor must be sheltered from precipitation.
- Dry and wet surface state compliance can be evaluated at all temperatures. Before a freezing temperature is reached on the sensor it should give a "wet" reading.
- To form ice, the pavement temperature must be below 32º F. The thermistor and thermometer may be used to check the air temperature.
- If required by the RPU, atmospheric sensors must be connected and working properly.

Equipment and Supplies Required

The following equipment and supplies are needed for testing dry/wet/ice conditions.

		
Heat gun ***Note: Do not hold the heat gun near the sensor surface***	Misting bottle filled with tap water	Nylon brush to clean the pins on top of the sensor
		
0.5 mm feeler gauge to measure film depth	Thermometer and thermistor to check air/pavement temperature	**Optional**: Shelter tent, such as collapsible ice fishing shelter

Field Testing Procedures – Test 2: Pavement Surface (Dry/Wet/Ice) Conditions

To test the pavement sensor for dry, wet and ice surface state performance, perform the following steps:

Step 1 Read all the manuals and manufacturer's literature on operating the participating sensor. Also read and observe all the safety precautions in Chapter 3.

Step 2 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the portable computer.

Step 3 Use water and paper towels to clean the pins on the top of the pavement sensor. Dry the subject sensor with the dry towels and heat gun.

Note: Dry the sensor with caution; do not hold the heat gun near the sensor surface.

- Perform this step on all components of the system that the system uses to determine surface state

Step 4 **Record** the following on the Testing and Maintenance Forms every two minutes until a dry pavement surface state reading is recorded:

- Visual determination of state of surface of pavement sensor
- State of pavement surface (from RPU)

Step 5 Shake the misting bottle and uniformly spray a 0.5 mm tap water film on the surface of all applicable sensors. Check the film thickness with the feeler gauge. If the film does not stay on the sensor, place a wet paper towel on the sensor and continue to perform the procedure and record use of the paper towel in the "Notes" area of the Forms.

Record the following on the Testing and Maintenance Form at two-minute intervals until the RPU reports the wet surface state or ten minutes have expired:

- Time of day
- Visual determination of state of surface of pavement sensor (dry/wet/ice)
- State of pavement surface (from RPU)

Step 6 If the pavement temperature is below 32º F, continue to record data until the RPU reports an ice condition. Conclude the test if RPU surface state does not change to ice in a reasonable amount of time (20 minutes).

The sensor fails this test and should be recalibrated or replaced if the pavement sensor does not report the wet or dry conditions. Ice detection should be determined based on a case-by-case basis according to the test conditions. If the sensor fails the first test, run the test an additional two times to verify the failure.

Figure 9. Cleaning Pavement Sensor Depression with a Paper Towel.

Figure 10. Spraying Tap Water on the Sensor Surface.

5.8 PAVEMENT SENSOR TESTS 3A AND 3B: FREEZING POINT OF PASSIVE AND ACTIVE PAVEMENT SENSORS

Depending on whether the ESS station has a pavement sensor that finds freezing point with a passive or an active sensor, the appropriate Field Test 3A or Field Test 3B should be run.

Field Test 3A: Freezing Point of Passive Sensors

For passive sensors to measure the freezing point of a particular brine solution on the sensor surface, the RPU or computer must be configured for that solution. The sensor generally determines the freezing point temperature by measuring the conductivity of the brine between the electrodes on the sensor surface. The relative conductivity values of five brine concentrations are shown in Appendix A. The test is run at 4% and 15% concentrations in order to understand sensor function at low and high salt concentrations.

Field Test 3B: Freezing Point of Active Sensors

An active pavement sensor can be used to determine the freezing point temperature of any brine or mixtures of brine. A Peltier device warms then cools the solution on the sensor. As the device cools the solution on the surface of the sensor, the temperature stabilizes as the liquid changes phase to solid. The RPU detects that the sensor has reached its freezing point and returns that temperature as the freezing point. This process is generally more accurate and is more robust because the freezing point is measured directly, not through conductivity values that are dependent on chemical type. However, the test takes longer to run because of the heating and cooling cycles.

5.9 PAVEMENT SENSOR TEST 3A: TESTING FREEZING POINT USING PASSIVE SENSORS

This test procedure will measure how well a passive sensor can detect a chemical solution's freezing point. The same type of chemical solution used in highway maintenance operations should be used for this test at a 4% concentration. The RPU is should already be configured for the typical chemical type, though this is verified in the test procedure.

The procedures to prepare the 4% chemical solution are listed in Appendix B.

Test Condition Notes:

- Ambient pavement temperature must be within the sensor's range for measuring freezing point. See Appendix B for brine properties and check with the manufacturer's documentation for temperature compliance.
- Passive sensors are very sensitive to concentration changes and film thickness. It is important to thoroughly clean the pavement sensor between runs with distilled water.

Equipment and Supplies Required

		
Device to shelter sensor from evaporation due to wind and sun (ice fishing shelter or 5-gallon bucket)	One gallon of distilled water	Heat gun ***Note: Do not hold the heat gun near the sensor surface***
		
0.5 mm feeler gauge to measure film depth	Misting bottle filled with 4% chemical solution	

Field Testing Procedures – Test 3A: Freezing Point Using Passive Sensors

To test passive pavement sensors for freezing point accuracy, perform the following steps:

Step 1 Read all the manuals and manufacturer's literature on operating the participating sensor. Also read and observe all the safety precautions in Chapter 3.

Step 2 Determine which chemical type the sensor is programmed to monitor.

Record the manufactures chemical solution type programming on the Testing and Maintenance Form, in the "Notes" section.

Record the chemical type and concentration of the chemical solution on the Testing and Maintenance Form in the "Chemical Solution Type:" section.

Step 3 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the portable computer.

Step 4 Repeatedly (5 times) flush the top of the sensor with distilled water and clean the pins on the top of the pavement sensor with paper towels. Clean and dry the subject sensor and surrounding area using paper towels. If necessary, carefully dry the sensor with the heat gun. Note: Do not hold the heat gun near the pavement sensor.

Note: Dry the sensor with caution; do not hold the heat gun near the sensor surface.

Step 5 Shake the bottle with the 4 percent chemical solution and spray a 0.5 mm film on the entire surface of the sensor. If the sensor has a well or depression, fill it with the solution. If the film does not stay on the sensor, place a paper towel on the sensor and continue to perform the procedure. If a paper towel is used record this in the "Notes" section of the Testing and Maintenance form.

Record the following on the Testing and Maintenance Form at two-minute intervals until the stability criteria is met:

- Time of day
- Freezing point (from RPU)

Stability criteria are met when the pavement sensor freezing point has varied less than 3.6º F (2.0º C) between four successive readings.

Step 6 Determine the average of the four stable readings for the pavement sensor freezing point and **record** the value on the Testing and Maintenance Forms. Repeat steps 4 and 5 for the 15% solution.

> The sensor fails this test if the average freezing point value of the pavement sensor and the freezing point of the chemical solution differ by more than 3.6º F (2.0º C). If the sensor fails the first test, run the test an additional two times to verify the failure.

5.10 PAVEMENT SENSOR TEST 3B: TESTING FREEZING POINT USING ACTIVE SENSORS

This test will measure the freezing point performance of active pavement sensors by exposing the sensor to 10% concentrations of chemical solution. The chemical solution type is not relevant to the outcome of this test because active sensors detect freezing point without any user input about chemical solution type.

The procedures to prepare the appropriate 4% and 15% chemical concentrations can be found in Appendix B. The procedures can also be used to prepare other concentrations if desired.

Test Conditions Notes:

- It is important to thoroughly clean the pavement sensor with distilled water.
- Some active sensors require data input from passive sensors. Perform the procedures on all applicable sensors.
- The following table shows the freezing points of various chemicals at 4 and 15% concentration:

Chemical Type	Freezing Point of 4% Concentration in ºC (ºF)	Freezing Point of 15% Concentration in ºC (ºF)
Sodium Chloride	27.7 (-2.4)	12.4 (-10.9)
Magnesium Chloride	27.8 (-2.3)	4.0 (-15.6)
Calcium Chloride	28.7 (-1.8)	12.2 (-11.0)

Equipment and Supplies Required


One gallon of distilled water


Device to shelter sensor from evaporation due to wind and sun (ice fishing shelter or 5-gallon bucket)


0.5 mm feeler gauge to measure film depth


Nylon brush to clean the pins on top of the sensor


Two misting bottles filled with 4 and 15% percent chemical solution

Field Testing Procedures – Test 3B: Freezing Point Using Active Sensors

To test an active pavement sensor for measuring freezing point temperatures, perform the following steps:

Step 1 Read all the manuals and manufacturer's literature on operating the participating sensor. Also read and observe all the safety precautions in Chapter 3.

Step 2 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the portable computer.

Step 3 Read the <u>temperature</u> (not freezing point) output values from the pavement sensor. If it is within the range for the active sensor to perform freeze/thaw cycles, proceed to Steps 4-6. See manufacturer's documentation for more information about this process.

This step determines whether the temperature conditions are sufficient to test an active sensor. If the temperature is too warm, the active sensor will not be able to freeze the solution. If it is too cold, the heating element will not thaw the chemical solution.

Step 4 Repeatedly flush the top of the applicable sensor(s) with distilled water and clean the pins on the top of the pavement sensor with paper towels. Clean and dry the subject sensor and surrounding area using paper towels.

Step 5 Shake the 4% misting bottle with and spray a 0.5 mm film on the applicable sensor(s). Use the feeler gauge to check the film thickness. If the film does not stay on the sensor, place a paper towel on the sensor and continue to perform the procedure. Use the "Notes" area of the Testing and Maintenance Forms for Pavement Sensors to document the use of the paper towel.

<u>**Record**</u> the type of chemical solution on the Testing and Maintenance Form under "Chemical Solution Type:"

Step 6 <u>**Record**</u> pavement sensor readings for this cycle and an additional two cycles. If the final two sensor readings are within 1 degree, the test is complete. Otherwise, <u>**record**</u> an additional two cycles before stopping the test.

Step 7 Determine the average of the latest two stable readings for the pavement sensor freezing point and <u>**record**</u> the value on the Testing and Maintenance Forms. Repeat steps 3-7 for the 15% solution.

> The sensor fails this test if the average freezing point value of the pavement sensor and the freezing point of the chemical solution differ by more than 3.0º F (1.7º C). If the sensor fails the first test of either solution, run the test an additional two times to verify the failure.

5.11 PAVEMENT SENSOR TEST 4: ICE BATH AT 32º F (OPTIONAL)

This test is recommended if there is doubt about the accuracy of the sensor specifically around water's freezing point (32 degrees). This test is marked "Optional" for a variety of reasons. First, the test takes a substantial amount of time to run. Warm weather conditions could make this test take even more time. A half-hour should be allowed for the ice bath to cool the pavement sensor to 32 degrees. During that time, the bath must be constantly stirred. If this test is to be run regularly, a device could be rigged to automatically stir the bath. Existing devices to mix mortar or ones used to stir cooking pots could be modified for this application.

Test Condition Notes:

- It is necessary to create the required temperature condition at the pavement sensor by using an ice water bath.
- This test may only be run on sensors with temperature sensing elements located near the surface of the sensor. If the temperature sensing element is too far below the surface, the test may take too long to conduct because of the time required to cool the sensor to a sufficient depth.
- The ambient temperature of the pavement should be between 32º F and 50º F. The test may still be performed under warmer temperatures, though it will take more time.
- Ice may be crushed before going out to the ESS site or at the site. To crush the ice on-site, put the ice in a canvas bag such as a bituminous sample bag and carefully crush the ice with the brick used in Field Test 1.

Equipment and Supplies Required

Thermal conducting paste

One handheld thermometer with precision thermistors

One gallon of chilled (below 40º F) distilled water

Stirring instrument such as a plastic slotted spoon

10-inch section of 12-inch diameter PVC pipe

10 pounds of crushed ice cubes

Plastic bag

Field Testing Procedures – Test 4: Ice Bath at 32º F (Optional)

To test the pavement sensor for temperature compliance, perform the following steps:

Step 1 Read all the manuals and manufacturer's literature on operating the participating sensor. Also read and observe all the safety precautions in Chapter 3.

Step 2 Use the procedures recommended by the RPU manufacturer to allow communication from the RPU to the portable computer.

Step 3 Clean and dry the subject sensor and surrounding area using paper towels.

Step 4 Place the PVC section around the pavement sensor. Slide the thermistor under the edge of the PVC so that the thermistor rests on the pavement sensor

Step 5 Put the large plastic bag in the PVC with the bag overlapping the edges of the PVC as shown in Figure 11. Fill the pipe section with the gallon of distilled water.

Step 6 Add enough crushed ice to produce a thick layer of slushy ice in the bath.

Step 7 Stir the mixture continuously and maintain the thick slushy ice layer.

Record the following on the Testing and Maintenance Form at two-minute intervals until the pavement sensor stabilizes within 1º F (0.6º C) of 32º F (0º C):

- Time of Day
- Pavement Temperature (From RPU)
- Thermistor temperature

If the reported sensor temperature does not decrease substantially or approach 32º F (0º C), after 10 minutes, stop the test.

Note: *Even if the sensor gets down to 32º F (0º C), the pavement sensor temperature readings could still decrease below that temperature. Continue to take readings until the temperature stabilizes within 1º F (0.6º C). Stop the test if the pavement sensor gives readings below 29º F (-1.6º C).*

The sensor fails this test and should be recalibrated or replaced if the temperature reported by the sensor does not stabilize within 3.0º F (-1.6º C) of 32º F (0.0º C).

Figure 11. Bag Placed Over PVC section.

Figure 12. Distilled Water Poured in PVC and Bag.

Figure 13. Ice Poured Into PVC and Plastic Bag.

6. FIELD TEST PROCEDURES AND CALIBRATION METHODS FOR ATMOSPHERIC SENSORS

Atmospheric sensors monitor meteorological information related to the road environment and assist with forecasting, detection and monitoring of weather and road conditions. Atmospheric sensors are located above and near the roadway at the ESS site. Independently, they can identify parameters, such as strong cross winds. In combination with pavement sensors, they can identify conditions, such as icy roads.

Typical sensors for RWIS systems at ESS sites are wind speed and direction, air temperature, dew point and humidity, precipitation and visibility. Other sensors that are sometimes used are solar radiation and atmospheric pressure. In order to maintain accuracy, atmospheric sensors need to be tested and/or calibrated in accordance with manufacturer-provided procedures.

Because atmospheric sensors are tested and calibrated using a variety of vendor-specified means, no standardized testing and calibration guidelines exist at this time. Temperature sensors can be tested statistically. Vendor contacts for some manufacturers and vendors are provided for agencies to obtain the most current calibration and testing procedures.

The following vendors make and/or distribute atmospheric sensors:

Belfort Instrument Company
727 South Wolfe Street
Baltimore, MD 21231
Tel. (410) 342-2626

Boschung America
P.O Box 8427
930 Cass St.
New Castle, PA 16101
Tel. (724) 658-3300

The Eppley Laboratory, Inc.
12 Sheffield Avenue
Newport, Rhode Island 02840
Tel. (401) 847-1020

Met One Instruments, Inc.
1600 Washington Blvd.
Grants Pass, OR 97526
Tel. (972) 412-4747

Optical Scientific Inc.
205 Perry Parkway, Suite 14
Gaithersburg, MD 20874
Tel. (301) 963-3630

ETI Optical Infrared
1317 Webster Avenue
Fort Collins, CO 80524
Tel. (970) 484-9393

R.M. Young Company
2801 Aero Park Drive
Traverse City, MI 49686
Tel. 231-946-3980

Rotronic Instrument Corp.
160 E. Main Street
Huntington, NY 11743
Tel. 631-427-3898

Surface Systems, Inc.
11612 Lilburn Park Road
St. Louis, MO 63146
Tel. (314) 569-1002

A. Thies GmbH & Co. KG
P.O. Box: 35 36
D-37025 Goettingen, Germany
Tel. +49 551 79001-0

Vaisala Inc.
PO Box 3659
Boulder, CO 80307
Tel. (303) 499-1701

Vaisala Inc.
Handar Business Unit
10-D Gill Street,
Woburn, MA 01801
Tel. (781) 933-4500

Two other resources for agencies to learn more about how sensors are tested and calibrated using alternative means, such as statistical means, are the CLARUS initiative and Meteorological Assimilation Data Ingest System (MADIS).

Clarus Initiative

Website: http://clarusinitiative.org

Contacts: James Pol (james.pol@fhwa.dot.gov)
U.S. DOT ITS Joint Program Office
202-366-4374

Paul Pisano (paul.pisano@fhwa.dot.gov)
Road Weather Management Program, FWHA
202-366-1301

MADIS

Website: http://www-sdd.fsl.noaa.gov/MADIS/

APPENDIX A
Phase Diagrams and Conductivity Curves for Brines

Because different chemicals have different properties, it may be beneficial to know about the properties of salt solutions to configure the RPU.

Solution Phase Diagrams

For the evaluators of pavement sensors to have some idea of the behavior of the various brines in regards to their concentrations and temperatures, Figure A-1 is provided for reference. As can be seen, each brine has its own characteristics.

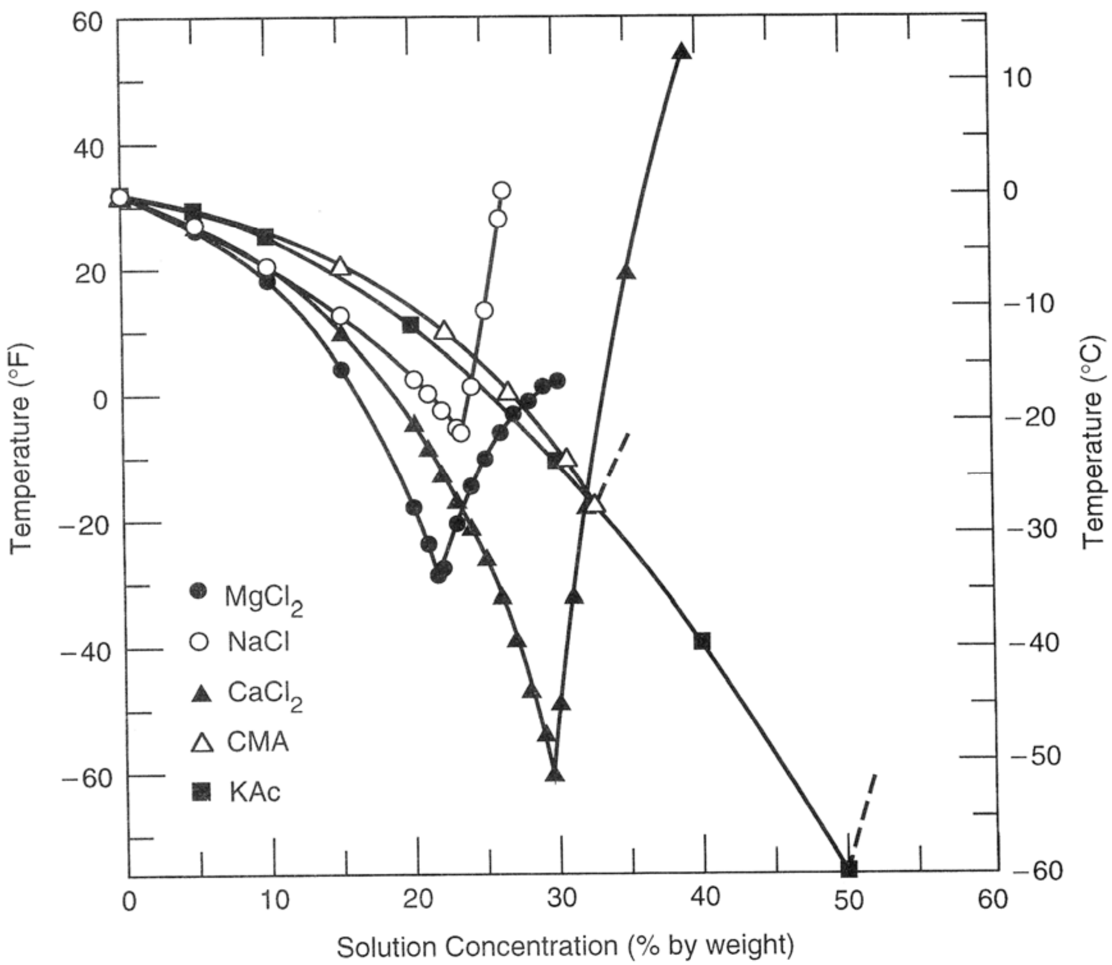


Figure A-1. Phase Diagrams of Five Brines

Conductivity Curves and Values for Solutions

During the research work for the Strategic Highway Research Program's (SHRP) project: "Development of Anti-Icing Technology" [3], laboratory studies were conducted to evaluate the utility of the SOBO-20 salinity tester for the semi-quantitative measurement of chemical solutions applied to pavement surfaces. The studies consisted of evaluating the type of response and range of detection for five different chemicals.

The results of the laboratory studies that included the conductivity measurements for the five chemical brines are presented in Tables G-5, G-6, and G-7. In addition, a composite presentation of the test data is set forth in Figure G-2.

This information is provided so that the evaluator can have a sense of the magnitude of the conductivity values for sodium chloride, magnesium chloride, and calcium solutions.

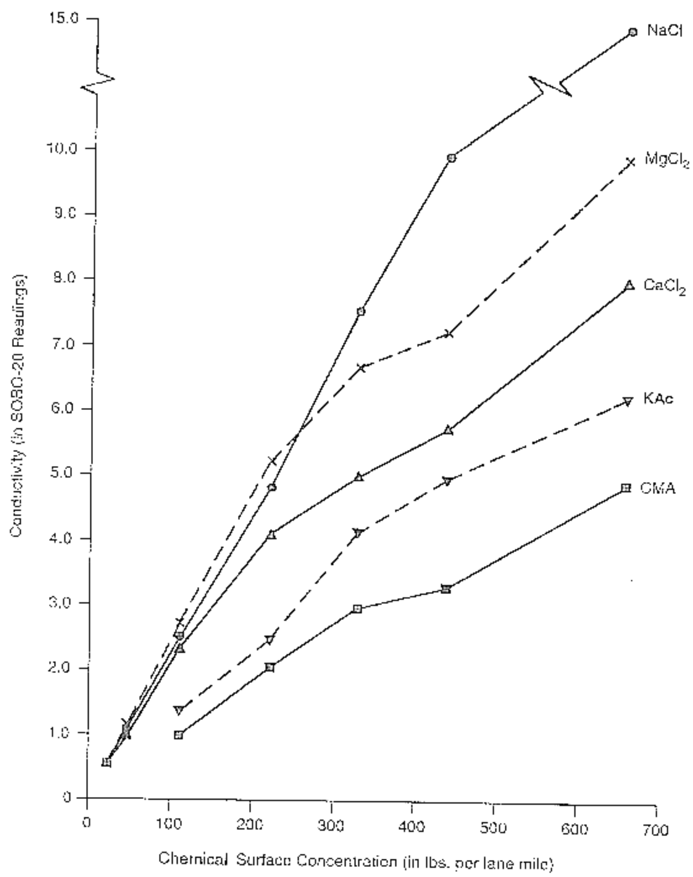


Figure A-2. SOBO-20 Readings versus Chemical Surface Concentration for Five Brines

Source: SHRP-H-385, Development of Anti-Icing Technology, Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

Table A-1. SOBO-20 Readings and Conductivity Values of Sodium Chloride Solutions

SOBO meter		Actual Reading [a]	Applied chemical surface concentration			Conductivity [a] (µS)
Observed Reading [a]	Scale Factor		(oz/yd^2)	(g/m^2)	(lb/lane mile)	
1	x ½	0.5	0.05	1.7	22	180
1	x 1	1	0.1	3.39	44	308
5	x 1/2	2.5	0.25	8.48	110	767
4.8	x 1	4.8	0.5	17	220	1,517
10	x 1/2	5	0.5	17	220	1,567
15	x 1/2	7.5	0.75	25.4	330	2,500
10	x 1	10	1	33.9	440	3,250
15	x 1	15	1.5	50.9	660	4,767

[a]Average of three determinations

Table A-2. Readings and Conductivity Values of Magnesium Chloride Solutions

SOBO meter		Actual Reading [a]	Applied chemical surface concentration			Conductivity [a] (µS)
Observed Reading [a]	Scale Factor		(oz/yd^2)	(g/m^2)	(lb/lane mile)	
1.00	x ½	0.50	0.05	1.7	22	135
1.00	x 1	1.00	0.10	3.39	44	250
2.75	x 1/2	1.38	0.25	8.48	110	602
5.25	x 1	5.25	0.50	17	220	1,185
10.00	x 1/2	5.00	0.50	17	220	1,222
13.38	x 1/2	6.69	0.75	25.4	330	2,712
7.25	x 1	7.25	1.0	33.9	440	3,500
10.00	x 1	10.00	1.50	50.9	660	5,075

[a]Average of three determinations

Table A-3. Readings and Conductivity Values of Calcium Chloride Solutions

SOBO meter		Actual Reading [a]	Applied chemical surface concentration			Conductivity [a] (µS)
Observed Reading [a]	Scale Factor		(oz/yd^2)	(g/m^2)	(lb/lane mile)	
1.00	x ½	0.50	0.05	1.7	22	135
1.00	x 1	1.00	0.10	3.39	44	250
4.90	x 1/2	2.45	0.25	8.48	110	602
3.90	x 1	3.90	0.50	17	220	1,185
8.80	x 1/2	4.40	0.50	17	220	1,222
10.00	x 1/2	5.00	0.75	25.4	330	2,712
5.75	x 1	5.75	1.0	33.9	440	3,500
8.00	x 1	8.00	1.50	50.9	660	5,075

[a]Average of three determinations

APPENDIX B
Procedures for Preparing Chemical Concentrations

In order to run the freezing point tests in Field Test Plan 4, it is necessary to prepare chemical solutions before going out to an ESS station.

This appendix contains procedures and tables of physical properties of the following chemical concentrations:

Sodium Chloride Brine Preparation

The following equipment and supplies are necessary to prepare the given concentrations of chemical brine to be used for testing the Freezing Point parameter of a pavement sensor.

- Supply of deiodized dry salt, such as table salt. Do not obtain salt from maintenance stockpiles as that salt has approximately 5% impure materials besides the salt.
- Supply of deionized or distilled water
- Scale that will weigh to the nearest gram or 0.03 oz.
- Supply of one-quart jars with lids. Jars must have a graduation for one quart.
- 1 liter graduated cylinder with hydrometer

The following procedures are to be used in preparing the various concentrations of salt brine:

Step 1 Fill a clean one-quart jar approximately 2/3 full of deionized or distilled water.

Step 2 From Table B-1, determine the amount of salt required to make one quart of solution at the desired concentration level.

Step 3 Weigh out the necessary amount of salt and gradually pour it into the jar while stirring the solution. Continue to stir until the salt is dissolved.

Step 4 Add deionized or distilled water to the jar to bring the level to the top of the jar. Screw the cap on the jar. Shake the jar to mix the solution.

Step 5 Remove the lid and pour some solution into a cylinder. Test the specific gravity of the solution with a hydrometer. An additional batch of solution may be necessary to use the Compare the readings with those in Table B-1.

Step 6 Replace the lid and label the jar with the chemical type and concentration.

Table B-1. Proportions for Preparing Sodium Chloride Solutions

% NaCl Concentration	Weight NaCl per quart of solution Oz (Grams)	Freezing Point Temperature ºC (º F)	Specific Gravity at 20.0º C (68.0º F)
1%	0.34 (9.6)	-0.59 (30.93)	1.007
4%	1.37 (38.9)	-2.4 (27.7)	1.0286
10%	3.58 (101.4)	-6.6 (20.2)	1.0726
15%	5.55 (157.4)	-10.9 (12.4)	1.1105
23%	9.00 (255.1)	-20.7 (-5.2)	1.1721

The following table may be used as a reference when preparing the sodium chloride solutions.

Table B-2. Physical Properties of Sodium Chloride

% NaCl by weight	Specific Gravity at 20.0º C (at 68.0º F)	Amount of NaCl per quart of solution (oz (grams))	Freezing Point (ºF)	Freezing Point (ºC)
1	1.0071	0.34 (9.56)	30.933	-0.593
2	1.0143	0.67 (19.12)	29.865	-1.186
3	1.0214	1.02 (28.96)	28.778	-1.790
4	1.0286	1.37 (38.90)	27.664	-2.409
5	1.0358	1.73 (48.93)	26.517	-3.046
6	1.0431	2.09 (59.15)	25.335	-3.703
7	1.0504	2.45 (69.46)	24.120	-4.378
8	1.0578	2.82 (79.97)	22.858	-5.079
9	1.0651	3.19 (90.57)	21.547	-5.807
10	1.0726	3.58 (101.35)	20.185	-6.564
11	1.0801	3.96 (112.24)	18.765	-7.353
12	1.0876	4.35 (123.31)	17.283	-8.176
13	1.0952	4.74 (134.48)	15.732	-9.038
14	1.1028	5.14 (145.83)	14.108	-9.940
15	1.1105	5.55 (157.38)	12.402	-10.888
16	1.1182	5.96 (169.02)	10.607	-11.885
17	1.1260	6.38 (180.85)	8.717	-12.935
18	1.1339	6.80 (192.77)	6.721	-14.044
19	1.1418	7.23 (204.98)	4.611	-15.216
20	1.1498	7.66 (217.28)	2.376	-16.458
21	1.1579	8.10 (229.68)	0.003	-17.776
22	1.1660	8.55 (242.36)	-2.517	-19.176
23	1.1721	9.00 (255.14)	-5.201	-20.667

Source: CRC handbook of Chemistry and Physics, 52nd edition, CRC Press, Boca Raton FL 1972, p. D-213 & D-214.

Magnesium Chloride Brine Preparation

Magnesium Chloride is usually used by highway agencies in liquid form. It is normally marketed in a 30% concentration. However, it can be purchased in solid (flake) form. In preparing solutions of magnesium chloride brine to be used for testing the freezing point parameter of a pavement sensor, it is recommended that liquid material be obtained and a hydrometer reading be taken of the material at 60º F. The material may then be diluted down to the desired concentration.

The following equipment and supplies are necessary to prepare the given concentrations of chemical brine to be used for testing the Freezing Point parameter of a pavement sensor.

- Supply of liquid magnesium chloride brine
- Supply of deionized or distilled water
- Supply of one-quart jars with lids.
- Two-quart glass container
- One liter graduated cylinder
- Hydrometer

The following procedures are to be used in preparing the various concentrations of magnesium chloride brine:

Step 1 Take a temperature reading of the supply of available magnesium chloride brine. If the temperature is not 60º F, either raise or lower the temperature to 60º F.

Step 2 Take a hydrometer reading of the magnesium chloride brine and record the data. If the solution has a concentration of 30%, the specific gravity reading should be 1.283. If not, use the hydrometer reading obtained in the calculations outlined below.

Step 3 From Table B-3, determine the specific gravity of the desired concentration.

Step 4 Perform the calculation as shown in Figure B-1 to determine the amount of dilution required.

Step 5 Pour 50 mL of the strong magnesium chloride brine in the two-quart container.

Step 6 Pour the calculated amount of deionized or distilled water from graduated cylinder into the two-quart container and mix the solution.

Step 7 Pour the diluted solution in a one quart jar and place the lid on the jar. Label the jar with the chemical type and concentration.

Step 8 The concentration of the diluted brine can be checked with a hydrometer reading if it is near 60º F.

Table B-3. Properties for Preparing Magnesium Chloride Brine

% $MgCl_2$ Concentration	Crystallization Temperature ºC (ºF)	Specific Gravity at 15.6º C (60.0º F)
4	-2.3 (27.8)	1.010
10	-7.8 (17.9)	1.086
15	-15.6 (4.0)	1.132
21.6	-33.3 (-28.0)	1.196
30	-16.1 (3.0)	1.283

The following formula may be used to determine the amount of deionized or distilled water needed to dilute a strong solution at 60º F.

- "% Strong" is the original concentration
- "% Weak" is the targeted concentration

$$\left[\frac{\%\ \text{Strong} - \%\text{Weak}}{\%\ \text{Weak}}\right] \text{X} \quad \text{Specific gravity of Strong Solution}$$

Figure B-1. Dilution Formula for Magnesium Chloride

Example: Assuming the strong brine has a concentration of 30%, its specific gravity is 1.283, and volume of 50 mL. Concentration of 10% is required of the dilution solution.

$$\left(\frac{30 - 10}{10}\right) * 1.283 = 2.566$$

2.566 X 50 mL = 128.3 mL

Add 128 mL of deionized or distilled water to the 50 mL of the 30% concentration of magnesium chloride brine to create a 10% concentration of magnesium chloride brine.

Figure B-2. Example of Magnesium Chloride Dilution

Table B-3 provides the properties of the various concentrations of magnesium chloride brine. If different concentrations are needed than those shown in Table B-3, the appropriate values can be obtained from Table B-5, Properties of Magnesium Chloride Brine. The above formula can be used to determine the amount of dilution required. Table B-6 provides the dilution factors and the amount of deionized or distilled water that must be added to either 30% or 21.6% concentrations of magnesium chloride brine. These two values are generally the concentrations that are marketed by vendors to highway agencies.

Table B-4. Dilution Factors and Amount of Water to be Added to Obtain Desired Solutions

Desired % $MgCl_2$ Concentration	30 % Concentration		21.6 % Concentration	
	Dilution Factors	mL of water to be added*	Dilution Factors	mL of water to be added*
4	8.340	417	5.262	263
10	2.566	128	1.387	69
15	1.283	64	0.526	26
21.6	0.499	25	-	0
30.0	-	0	N/A	N/A

*Amount of deionized or distilled water to be added to 50 mL of concentration of magnesium chloride brine required to create the desired concentration of magnesium chloride brine.

Table B-5. Properties of Magnesium Chloride Brine

% by Weight	Specific Gravity at 15.6º C (60.0º F)	Freezing Point Celsius	Freezing Point Fahrenheit
5	1.013	-2.11	26.4
6	1.051	-3.09	25.0
7	1.060	-4.72	23.5
8	1.069	-5.67	21.8
9	1.070	-6.67	20.0
10	1.086	-7.83	17.9
11	1.096	-9.05	15.7
12	1.105	-10.50	13.1
13	1.114	-12.10	10.3
14	1.123	-13.70	7.3
15	1.132	-15.90	4.0
16	1.142	-17.60	0.4
17	1.151	-19.70	-3.5
18	1.161	-22.10	-7.7
19	1.170	-25.60	-12.2
20	1.180	-27.40	-17.2
21	1.190	-30.50	-23.0
22	1.200	-32.80	-27.0
23	1.210	-28.90	-20.0
24	1.220	-25.60	-14.0
25	1.230	-23.30	-10.0
26	1.241	-21.10	-6.0
27	1.251	-19.40	-3.0
28	1.262	-18.30	-1.0
29	1.273	-17.20	1.0
30	1.283	-16.70	3.0

Source: Chemical Deicer Specifications for the Pacific Northwest States of Idaho, Montana, Oregon, Washington State, p 25.

Calcium Chloride Brine Preparation

Calcium Chloride is usually used by highway agencies in liquid form. It is normally marketed in a 30% concentration. However, it can be purchased in solid (flake) form. In preparing solutions of calcium chloride brine to be used for testing the Freezing Point parameter of a pavement sensor, it is recommended that liquid material be obtained, and a hydrometer reading be taken of the material at 68º F (20° C). The material than be diluted down to the desired concentration.

The following equipment and supplies are necessary to prepare the given concentrations of chemical brine to be used for testing the Freezing Point parameter of a pavement sensor.

- Supply of liquid calcium chloride brine
- Supply of deionized or distilled water
- Supply of one-quart jars with lids.
- A two-quart glass container
- One liter graduated cylinder
- Hydrometer

The following procedures are to be used in preparing the various concentrations of calcium chloride brine:

Step 1 Take a temperature reading of the supply of available calcium chloride brine. If the temperature is not 68º F, either raise or lower the temperature to 68º F.

Step 2 Take a hydrometer reading of the calcium chloride brine and recorded the data. If the solution has a concentration of 30%, the specific gravity reading should be 1.2816. If not, use the hydrometer reading obtained, in the calculations outlined below.

Step 3 From Table B-3, determine the specific gravity of the desired concentration.

Step 4 Perform the calculation as shown in Figure B-1 to determine the amount of dilution required.

Step 5 Pour 50 mL of the strong magnesium chloride brine in the two-quarter container.

Step 6 Pour the calculated amount of deionized or distilled water from graduated cylinder into the two-quart container and mix the solution.

Step 7 Pour the diluted solution in a one quart jar and place the lid on the jar. Label the jar with the chemical type and concentration.

Step 8 The concentration of the diluted brine can be checked with a hydrometer reading if it is near 68º F.

Table B-6. Properties for Preparing Calcium Chloride Brine

% $CaCl_2$ Concentration	Crystallization Temperature in ºC (ºF)	Specific Gravity at 20.0º C (68.0º F)
1	-0.44 (31.21)	1.0065
4	-1.82 (28.73)	1.0316
10	-5.86 (21.45)	1.0835
15	-11.01 (12.18)	1.1292
30	-41.00 (-41.80)	1.2816

Source: CRC Handbook of Chemistry and Physics, 52nd edition, CRC Press, Boca Raton, FL 1972, p. D 224

The following formula may be used to determine the amount of deionized or distilled water needed to dilute a strong solution at 68º F.

- "% Strong" is the original concentration
- "% Weak" is the targeted concentration

$$\left[\frac{\%\text{ Strong} - \%\text{Weak}}{\%\text{ Weak}}\right] \text{X Specific gravity of Strong Solution}$$

Figure B-3. Dilution Formula for Calcium Chloride

Example: Assuming the strong brine has a concentration of 30%, its specific gravity is 1.283, and volume of 50 mL. Concentration of 10% is required of the dilution solution.

$$\left(\frac{30 - 10}{10}\right) * 1.2816 = 2.5632$$

2.566 X 50 mL = 128.3 mL

Add 128 mL of deionized or distilled water to the 50 mL of the 30% concentration of calcium chloride brine to create a 10% concentration of calcium chloride brine.

Figure B-4. Example of Calcium Chloride Dilution

Table B-6 provides the properties of the various concentrations of calcium chloride brine. If different concentrations are needed than those shown in Table B-6, the appropriate values can be obtained from Table B-8, Properties of Calcium Chloride Brine. The above formula can be used to determine the amount of dilution required. Table B-7 provides the dilution factors and the amount of deionized or distilled water that must be added to either 30% or 21.6% concentrations of calcium chloride brine. These two values are generally the concentrations that are marketed by vendors to highway agencies.

Table B-7. Dilution Factors and Amount of Water to be Added to Obtain Desired Solutions

Desired % $CaCl_2$ Concentration	30 % Concentration		21.6 % Concentration	
	Dilution Factors	mL of water to be added*	Dilution Factors	mL of water to be added*
1	37.166	1858	1	37.166
4	8.3304	417	4	8.3304
10	2.563	128	10	2.563
15	1.2816	64	15	1.2816
30	0	0	30	N/A

*Amount of deionized or distilled water to be added to 50 mL of respective concentration of magnesium chloride brine required to create the desired concentration of magnesium chloride brine.

Table B-8. Properties of Calcium Chloride Brine

Percent by Weight	Specific Gravity at 68° F (20° C)	Freezing Point (Celsius)	Freezing Point (Fahrenheit)
1	1.0065	-0.44	31.21
2	1.0148	-0.88	30.42
3	1.0232	-1.33	29.61
4	1.0316	-1.82	28.73
5	1.0401	-2.35	27.78
6	1.0486	-2.93	26.73
7	1.0572	-3.57	25.57
8	1.0659	-4.28	24.31
9	1.0747	-5.04	22.93
10	1.0835	-5.86	21.45
11	1.0923	-6.74	19.87
12	1.1014	-7.70	18.14
13	1.1105	-8.72	16.30
14	1.1198	-9.83	14.31
15	1.1292	-11.01	12.18
16	1.1386	-12.28	9.90
17	1.1482	-13.65	7.43
18	1.1579	-15.11	4.80
19	1.1677	-16.70	1.94
20	1.1775	-18.30	-0.94
21	1.1876	-20.00	-4.00
22	1.1976	-21.70	-7.06
23	1.2078	-23.50	-10.30
24	1.2180	-25.30	-13.54
25	1.2284	-27.50	-17.50
26	1.2388	-29.70	-21.46
27	1.2494	-32.20	-25.96
28	1.2600	-34.70	-30.46
29	1.2708	-37.85	-36.13
30	1.2816	-41.00	-41.80

Source: Chemical Deicer Specifications for the Pacific Northwest States of Idaho, Montana, Oregon, Washington State, p 25.

APPENDIX C
Testing and Maintenance Forms for Pavement Sensors

Name of operator: ____

Agency: ______________________________ Date: ___________________

Location of ESS:____

Location of Pavement Sensor (if multiple sensors): ______________________

Sensor Manufacturer: _____________ Sensor Serial Number: ________________

Initial Pavement Sensor Readings

Pavement Sensor Temperature	_______	Air Temperature	_______
Pavement Sensor Surface State	_______	Dew Point	_______
Pavement Sensor Freezing Point	_______		

Weather Conditions ______________________________________

Observation of Pavement Sensor on Arrival

Action Recommendation (to be completed after testing)

Pavement Sensor Test 1: Pavement Temperature at Ambient Conditions

Notes:

____

____

____

____

Reading Number	Time of Day	Pavement Sensor Reading (2.5" from Sensor)	Thermistor Reading (2.5" from Sensor)	Pavement Sensor Reading (On Pavement Sensor)	Thermistor Reading (On Pavement Sensor)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					

Average				

Pavement Sensor Test 2: Pavement Surface (Dry/Wet/Ice) Conditions

Reading	Time of Day	Visual Surface State Observation (Circle one)	Pavement Surface State (From RPU)
1		dry / wet / ice	
2		dry / wet / ice	
3		dry / wet / ice	
4		dry / wet / ice	
5		dry / wet / ice	
6		dry / wet / ice	
7		dry / wet / ice	
8		dry / wet / ice	
9		dry / wet / ice	
10		dry / wet / ice	
11		dry / wet / ice	
12		dry / wet / ice	
13		dry / wet / ice	
14		dry / wet / ice	
15		dry / wet / ice	

Notes:

Pavement Sensor Test 3A: Freezing Point of Passive Sensors

Chemical Solution RPU is Programmed For: ________________________

Chemical Solution Used in Test: _______________________________

Run 1

Reading Number	Time of Day	Freezing Point (Pavement Sensor Reading)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		

Avg		

Run 2 (If Necessary)

Reading Number	Time of Day	Freezing Point (Pavement Sensor Reading)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		

Avg		

Run 3 (If Necessary)

Reading Number	Time of Day	Freezing Point (Pavement Sensor Reading)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		

Avg		

Notes:

____

____

Pavement Sensor Test 3B: Freezing Point of Active Sensors

Chemical Solution RPU is Programmed For: ________________________

Chemical Solution Used in Test: _______________________________

Run 1

Reading Number	Time of Day	Freezing Point (Pavement Sensor Reading)
1		
2		
3		
4		
5		
Avg		

Run 2 (If Necessary)

Reading Number	Time of Day	Freezing Point (Pavement Sensor Reading)
1		
2		
3		
4		
5		
Avg		

Run 3 (If Necessary)

Reading Number	Time of Day	Freezing Point (Pavement Sensor Reading)
1		
2		
3		
4		
5		
Avg		

Notes:

Pavement Sensor Test 4: Ice Bath at 32º F

Reading Number	Time of Day	Pavement Sensor Reading	Thermistor Reading
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Notes: