A Thesis

entitled

A Sensor for Ice Monitoring on Bridge Superstructures

by

Clinton J. Mirto

Submitted to the Graduate Faculty as a partial fulfillment of the requirements for the

Master of Science Degree in Civil Engineering

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The University of Toledo

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An Abstract of

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In January 2015, another major icing event occurred on the Veterans’ Glass City Skyway. This event required all northbound lanes to close for a duration of 8 hours due to ice shedding. The shedding event occurred in a manner that has never been observed in field experiments or in previous icing events on the bridge. In the January 2015 event, a thin ice layer shed released in small fragments rather than the typical large sheet shedding observed in the past. The January 2015 icing event is documented thoroughly for the first time in this thesis.

A weather monitoring system that provides early warning and continuous weather monitoring is only as accurate and reliable as incoming data provided by the sensors implemented on the bridge. There is data pertaining to the stay sheath condition throughout winter weather events, such as icing, that is considered invaluable and is not captured by any commercial sensor. The variables pertaining to the condition of the stay sheath that need to be captured include the presence of water and thickness of ice accumulation on the sheath itself. The University of Toledo icing research team has designed and developed two sensors to capture this information. The design,
development and results from both the laboratory and field setting are presented in this thesis.

This thesis will also discuss shedding observations made from the 2014-2015 ice accumulation and shedding experiments performed at the Scott Park field station. Although these particular experiments were primarily done to expose the new revised design of the University of Toledo Presence and State sensor to freeze thaw cycles, there were valuable and insightful observations made pertaining to ice shedding on stainless steel sheaths.
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I also would like to thank the Ohio Department of Transportation for their financial support throughout the research process.
# Table of Contents

Chapter 1 - Introduction........................................................................................................ 1  
1.1  Introduction to Problem ............................................................................................... 1  
1.2  Known Bridges with Icing/Wet Snow Issues.............................................................. 3  
  1.2.1  Leonard P. Zakim Bunker Hill Bridge ................................................................. 3  
  1.2.2  Penobscot Narrows Bridge ..................................................................................... 4  
  1.2.3  Port Mann Bridge .................................................................................................. 4  
  1.2.4  Ravenel Bridge ...................................................................................................... 5  
  1.2.5  Severn Bridge ....................................................................................................... 5  
  1.2.6  Uddevalla Bridge .................................................................................................. 6  
1.3  Objectives ..................................................................................................................... 6  
1.4  Organization of Thesis ................................................................................................. 8  

Chapter 2 – Icing on Stainless Steel Sheaths ..................................................................... 10  
  2.1  General Bridge Background ...................................................................................... 10  
  2.2  Problem Statement ..................................................................................................... 12  
  2.3  Historical Weather History ......................................................................................... 13  
    2.3.1  December 2007 .................................................................................................... 13  
    2.3.2  March 2008 ......................................................................................................... 14  
    2.3.3  December 2008 .................................................................................................. 14  
    2.3.4  January 2009 ...................................................................................................... 15  
    2.3.5  February 2011 .................................................................................................... 15  
    2.3.6  Lessons Learned from Historical Icing Events .................................................. 16  
  2.4  Technology Matrix and Technology Selection .......................................................... 17  
  2.5  University of Toledo Testing Facilities ..................................................................... 19  
    2.5.1  The University of Toledo’s Icing Tunnel ............................................................ 19  
    2.5.2  The University of Toledo’s Field Experiment Station ........................................ 22
2.6 Experiments & Results

2.6.1 Ice Accumulation and Shedding Experiments

2.6.2 Coating Experiments

2.6.2.1 University of Toledo Icing Tunnel Coating Experiments

2.6.2.2 Field Station Coating Experiments

2.6.3 Thermal Experiments

2.6.4 Chemical Experiments at the Field Station

2.6.5 Summary of Experiments

2.7 Instrumentation of the Veterans’ Glass City Skyway

2.8 Real Time Weather Monitoring System

2.9 Conclusion

Chapter 3 – January 2015 Icing Event

3.1 Introduction

3.2 Daily Description of the January 2015 Event

3.3 Conclusion

Chapter 4 – Sensor Evaluation and Development

4.1 Introduction

4.2 Snow and Ice Maker

4.2.1 The Science behind Snow Making

4.2.2 Externally Mixed Versus Internally Mixed Snow Machines

4.2.3 The University of Toledo Snow Machine Design

4.3 The University of Toledo Presence and State Sensor

4.3.1 Importance of the UT Presence and State Sensor

4.3.2 How the UT Presence and State Sensor Works

4.3.3 UT Presence and State Sensor Prototype Design

4.3.4 UT Presence and State Sensor Prototype Ice Experiments

4.3.4.1 Icing Experiment, February 16, 2013 – February 17, 2013

4.3.5 UT Presence and State Sensor Prototype Wet Snow Experiments

4.3.6 UT Presence and State Sensor Revised Design

4.3.7 UT Presence and State Sensor Revised Design Lab Results

4.3.8 UT Presence and State Sensor Revised Design Ice Experiments

4.3.8.1 Icing Experiment, March 6, 2015 – March 7, 2015
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Technologies to be Tested</td>
<td>199</td>
</tr>
<tr>
<td>2.2</td>
<td>Coating Experiment Results (Likitkumchorn, 2014)</td>
<td>28</td>
</tr>
<tr>
<td>2.3</td>
<td>Uncertainties that Needed to be Resolved and Corresponding Sensors</td>
<td>41</td>
</tr>
<tr>
<td>3.1</td>
<td>Icing Event History</td>
<td>49</td>
</tr>
<tr>
<td>3.2</td>
<td>Northbound Lane Closure</td>
<td>55</td>
</tr>
</tbody>
</table>
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Cable-stayed Bridges vs. Historical Icing.</td>
<td>3</td>
</tr>
<tr>
<td>2-1</td>
<td>The Veterans’ Glass City Skyway ..................................................................</td>
<td>11</td>
</tr>
<tr>
<td>2-2</td>
<td>One of the Veterans’ Glass City Skyway Lighting Schematics</td>
<td>12</td>
</tr>
<tr>
<td>2-3</td>
<td>University of Toledo Icing Tunnel SolidWorks Design</td>
<td>20</td>
</tr>
<tr>
<td>2-4</td>
<td>The University of Toledo Icing Tunnel ....................................................</td>
<td>20</td>
</tr>
<tr>
<td>2-5</td>
<td>Misting System and Camera in Test Section ...............................................</td>
<td>21</td>
</tr>
<tr>
<td>2-6</td>
<td>Mounting System with Test Specimen</td>
<td>22</td>
</tr>
<tr>
<td>2-7</td>
<td>Overhead View of Outdoor Field Experiment Station .....................................</td>
<td>23</td>
</tr>
<tr>
<td>2-8</td>
<td>Stay Sheath Orientation and Angle during Experiments ..................................</td>
<td>23</td>
</tr>
<tr>
<td>2-9</td>
<td>Typical Ice Accumulation Setup ....................................................................</td>
<td>26</td>
</tr>
<tr>
<td>2-10</td>
<td>Water in the Interstice between the Sheath and Ice Layer</td>
<td>27</td>
</tr>
<tr>
<td>2-11</td>
<td>Formation of Water Puddles – Uncoated .....................................................</td>
<td>29</td>
</tr>
<tr>
<td>2-12</td>
<td>Formation of Ice Layer – Uncoated ................................................................</td>
<td>29</td>
</tr>
<tr>
<td>2-13</td>
<td>Specimen at Conclusion of Test – Uncoated ................................................</td>
<td>29</td>
</tr>
<tr>
<td>2-14</td>
<td>Individual Water Droplets Beginning to Freeze, Typical for Coated ...............</td>
<td>30</td>
</tr>
<tr>
<td>2-15</td>
<td>Uneven Ice Layer, Typical for Coated .......................................................</td>
<td>30</td>
</tr>
<tr>
<td>2-16</td>
<td>Specimen at Conclusion of Test, Typical for Coated .....................................</td>
<td>30</td>
</tr>
<tr>
<td>2-17</td>
<td>Experimental Setup .......................................................................................</td>
<td>31</td>
</tr>
<tr>
<td>2-18</td>
<td>Frozen Droplets over the Coating ..................................................................</td>
<td>32</td>
</tr>
<tr>
<td>2-19</td>
<td>VGCS Stay Sheath Cross-Section .....................................................................</td>
<td>33</td>
</tr>
<tr>
<td>2-20</td>
<td>Thermal Experiment Setup ................................................................................</td>
<td>34</td>
</tr>
<tr>
<td>2-21</td>
<td>Deicing Pattern in Thermal Test ...................................................................</td>
<td>35</td>
</tr>
<tr>
<td>2-22</td>
<td>Ice Accumulation during Thermal Anti-icing Experiment ..................................</td>
<td>36</td>
</tr>
<tr>
<td>2-23</td>
<td>Chemical De-icing Pattern ............................................................................</td>
<td>37</td>
</tr>
<tr>
<td>2-24</td>
<td>Icing Pattern for Anti-Icing Chemical Experiment ........................................</td>
<td>38</td>
</tr>
<tr>
<td>2-25</td>
<td>Thermistor Array Locations on the VGCS .....................................................</td>
<td>42</td>
</tr>
<tr>
<td>2-26</td>
<td>Instrumentation Tower Location .....................................................................</td>
<td>43</td>
</tr>
<tr>
<td>2-27</td>
<td>Screenshot of the Dashboard Tab of the Monitoring System ............................</td>
<td>46</td>
</tr>
<tr>
<td>3-1</td>
<td>Distribution of Ice on January 21, 2015 ....................................................</td>
<td>50</td>
</tr>
<tr>
<td>3-2</td>
<td>Global vs. Diffuse Radiation, January 22, 2015 .........................................</td>
<td>51</td>
</tr>
<tr>
<td>3-3</td>
<td>Distribution of Ice on January 22, 2015 ....................................................</td>
<td>52</td>
</tr>
<tr>
<td>3-4</td>
<td>Global vs. Diffuse Radiation, January 22, 2015 .........................................</td>
<td>53</td>
</tr>
<tr>
<td>3-5</td>
<td>Photographs from January 23, 2015 ................................................................</td>
<td>54</td>
</tr>
<tr>
<td>4-1</td>
<td>Ambient Temperature and Humidity Correlation to Wet Bulb Temperatures ..........</td>
<td>60</td>
</tr>
<tr>
<td>Page</td>
<td>Section</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>4-2</td>
<td>Snow Maker, Side View</td>
<td></td>
</tr>
<tr>
<td>4-3</td>
<td>Snow Maker, Top View</td>
<td></td>
</tr>
<tr>
<td>4-4</td>
<td>Place Holder for Schematic</td>
<td></td>
</tr>
<tr>
<td>4-5</td>
<td>Snow Maker spraying Wet Snow onto a Specimen</td>
<td></td>
</tr>
<tr>
<td>4-6</td>
<td>Goodrich Ice Detector Schematic</td>
<td></td>
</tr>
<tr>
<td>4-7</td>
<td>Leaf Wetness Sensor</td>
<td></td>
</tr>
<tr>
<td>4-8</td>
<td>Basic Open Circuit Schematic</td>
<td></td>
</tr>
<tr>
<td>4-9</td>
<td>Circuit for the UT Presence and State Sensor</td>
<td></td>
</tr>
<tr>
<td>4-10</td>
<td>UT Presence and State Sensor, Prototype</td>
<td></td>
</tr>
<tr>
<td>4-11</td>
<td>UT Presence and State Sensor Orientation on Field Specimens</td>
<td></td>
</tr>
<tr>
<td>4-12</td>
<td>Icing Experiment with UT Presence and State Sensor</td>
<td></td>
</tr>
<tr>
<td>4-13</td>
<td>UT Presence and State Prototype Sensor Data</td>
<td></td>
</tr>
<tr>
<td>4-14</td>
<td>HDPE Specimen Setup</td>
<td></td>
</tr>
<tr>
<td>4-15</td>
<td>HDPE Specimen and Frame</td>
<td></td>
</tr>
<tr>
<td>4-16</td>
<td>Wet Snow Accumulation on the Top of HDPE Sheath</td>
<td></td>
</tr>
<tr>
<td>4-17</td>
<td>Data Output from the LWS and the UT Presence and State Sensor</td>
<td></td>
</tr>
<tr>
<td>4-18</td>
<td>Data Output from the top UT Presence and State Sensor</td>
<td></td>
</tr>
<tr>
<td>4-19</td>
<td>Snow Shedding on the West Side of HDPE Specimen</td>
<td></td>
</tr>
<tr>
<td>4-20</td>
<td>Tapes used in the Revised Design of the UT Presence and State Sensor</td>
<td></td>
</tr>
<tr>
<td>4-21</td>
<td>Wire Connections and Caulking for Revised Sensor Design</td>
<td></td>
</tr>
<tr>
<td>4-22</td>
<td>The Creation Stages of the UT Presence and State Sensor</td>
<td></td>
</tr>
<tr>
<td>4-23</td>
<td>Schematic for the Revised Design of the UT Presence and State Sensor</td>
<td></td>
</tr>
<tr>
<td>4-24</td>
<td>Photographs from Laboratory Experiment</td>
<td></td>
</tr>
<tr>
<td>4-25</td>
<td>Results from the UT Presence and State Sensor Laboratory Experiment</td>
<td></td>
</tr>
<tr>
<td>4-26</td>
<td>Photosensor Orientation on Field Specimens</td>
<td></td>
</tr>
<tr>
<td>4-27</td>
<td>Scott Park Experimental Setup</td>
<td></td>
</tr>
<tr>
<td>4-28</td>
<td>Top UT Ice Presence and State Sensor vs. Ambient Air Temperature</td>
<td></td>
</tr>
<tr>
<td>4-29</td>
<td>East UT Ice Presence and State Sensor vs. Ambient Air Temperature</td>
<td></td>
</tr>
<tr>
<td>4-30</td>
<td>West UT Ice Presence and State Sensor vs. Ambient Air Temperature</td>
<td></td>
</tr>
<tr>
<td>4-31</td>
<td>Bottom UT Ice Presence and State Sensor vs. Ambient Air Temperature</td>
<td></td>
</tr>
<tr>
<td>4-32</td>
<td>VGCS Specimen with Ice Accumulation of 1/4”</td>
<td></td>
</tr>
<tr>
<td>4-33</td>
<td>Solar Radiation Causing Ice to Sublimate on East and Top of Sheath</td>
<td></td>
</tr>
<tr>
<td>4-34</td>
<td>Photographs from March 7 Sheding Event</td>
<td></td>
</tr>
<tr>
<td>4-35</td>
<td>Top UT Ice Presence and State Sensor vs. Ambient Air Temperature</td>
<td></td>
</tr>
<tr>
<td>4-36</td>
<td>East UT Ice Presence and State Sensor vs. Ambient Air Temperature</td>
<td></td>
</tr>
<tr>
<td>4-37</td>
<td>West UT Ice Presence and State Sensor vs. Ambient Air Temperature</td>
<td></td>
</tr>
<tr>
<td>4-38</td>
<td>Bottom UT Ice Presence and State Sensor vs. Ambient Air Temperature</td>
<td></td>
</tr>
<tr>
<td>4-39</td>
<td>VGCS Specimen with Ice Accumulation between 3/8” and 1/2”</td>
<td></td>
</tr>
<tr>
<td>4-40</td>
<td>Photographs from March 24 Sheding Event</td>
<td></td>
</tr>
<tr>
<td>4-41</td>
<td>Corrosion Effects on the Copper Strips</td>
<td></td>
</tr>
<tr>
<td>4-42</td>
<td>AGKU 1500 GI Ultrasonic Sensor</td>
<td></td>
</tr>
<tr>
<td>4-43</td>
<td>SR50AT Sonic Ranging Sensor</td>
<td></td>
</tr>
<tr>
<td>4-44</td>
<td>Photographs from March 6, 2015 – March 7, 2015 Icing Experiment</td>
<td></td>
</tr>
<tr>
<td>Page</td>
<td>Section</td>
<td>Page Number</td>
</tr>
<tr>
<td>------</td>
<td>----------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>4-45</td>
<td>UT Optical Sensor Calibration Process</td>
<td>114</td>
</tr>
<tr>
<td>4-46</td>
<td>UT Optical Sensor Calculation Process</td>
<td>1144</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Introduction to Problem

Harsh winter weather events, such as icing or wet snow, affect numerous bridges with above deck structure all over the world. In these weather events, the ice or wet snow accumulates on the superstructure over a period of time. The ice then may persist on the superstructure for days until one of the shedding triggers occur. The shedding triggers include: 1.) Ambient air temperature rising above freezing (32°F), 2.) Solar radiation reaching a critical level, and 3.) A combination of rising temperature and solar radiation. Shedding can occur in numerous other ways considering weather conditions rarely duplicate themselves during icing and wet snow events, however, past events have shown the three aforementioned triggers are the most common. When ice persists, travelling lanes on the bridge typically need to be closed due to the potential of falling ice. Lane closures are performed as a safety precaution, however, they result in inconvenience to the travelling public and depending on the location of the bridge, may also have economic impacts. Shedding of accumulations is a safety hazard to the
travelling public and reports pertaining to bridges that have experienced such weather events usually mention vehicles being damaged from falling ice or wet snow sheets.

Although ice or wet snow collects on all superstructure, this thesis will focus on cable-stayed bridges because the overarching problem to be addressed is the Veterans’ Glass City Skyway in Toledo, Ohio. A few of the cable-stayed bridges that have been affected include the Leonard P. Zakim Bunker Hill Bridge in Boston, MA., Penobscot Narrows Bridge near Prospect, ME., Port Mann Bridge near Vancouver, B.C., Ravenel Bridge in Charleston, SC, Uddevalla Bridge in Uddevalla, Sweden, and the Veterans’ Glass City Skyway in Toledo, Ohio. There are 36 cable-stayed bridges that are currently open to traffic, under construction or proposed located in the United States and lower tier of Canada. Over 85% (32 of the 36) of these North American cable-stayed bridges are situated in or close to areas that have historically had damaging winter storms, as seen in Figure 1-1 below (Mirto et al., 2015). When taking this into consideration, there is a need to understand how these winter weather events happen, how to mitigate their impact, and to collect data pertaining to them.
1.2 Known Bridges with Icing/Wet Snow Issues

1.2.1 Leonard P. Zakim Bunker Hill Bridge

The Leonard P. Zakim Bunker Hill Bridge crosses the Charles River in Boston, Massachusetts. In March of 2005, the Boston area experienced winter conditions that caused the cable sheaths of the Leonard P. Zakim Bunker Hill Bridge to ice. The ice then fell off of the stay sheaths in large sheets and onto the roadway below. Officials and design engineer considered this weather to be a “fluke,” thus, no mitigation technology was investigated (Daniel, 2005).
1.2.2 Penobscot Narrows Bridge

The Penobscot Narrows Bridge allows traffic to cross over the Penobscot River between Verona Island, ME and Prospect, ME (Penobscot Narrows Bridge and Observatory, 2014). The bridge was completed and opened in 2006 and experienced weather that caused bridge closure due to icing for the first time in 2014. Due to the irregular occurrence of icing, the state DOT has taken an observation approach, thus, no technology is currently being investigated or deployed (Gluckman, 2014).

1.2.3 Port Mann Bridge

The Port Mann Bridge is an A-type cable stayed bridge that allows traffic to cross the Fraser River in Vancouver, B.C.. The bridge was opened to traffic in 2012 and experienced winter conditions that resulted in the accretion and shedding of wet snow in December 2012. Numerous technologies have been investigated, which includes: heating of the stays, the use of water, the use of a helicopter, cable collars, coatings, chemicals, sensors, etc. Currently, cable collars have been deployed on several stays (Meiszner, 2013). In addition to the cable collars, a monitoring system was setup in order to provide an early warning and continuous event monitoring with local weather sensors, however, they decided to mothball the monitoring system in order to pursue active control. The Port Mann Bridge staff includes an expert meteorologist that monitors the weather and informs operations personnel when to deploy the cable collars throughout wet snow events.
1.2.4 Ravenel Bridge

The Ravenel Bridge connects Mt Pleasant, SC and peninsular downtown Charleston SC. In late January 2014, the bridge experienced weather that caused the cable stays to ice for the first time. Once the stays warmed up, ice began to shed causing damage to numerous vehicles passing below. There are reports of ice sheets as large as 8 to 10 feet falling from the cable sheaths (ABCNews4 WCIV-TV., 2014). The second event came less than one month later in February 2014. No vehicle damages were reported, however, the bridge was completely closed to traffic. Currently, there is not a technology deployed on this bridge, but they have filed for a grant from the Federal Emergency Management Agency in order to pursue solutions to the problem (Tiny electric pulses could keep dangerous ice off Ravenel Bridge cables, practical, 2014).

1.2.5 Severn Bridge

The Severn Bridge is a suspension bridge that stretches between England and Wales. This bridge was open to traffic in 1996 (Daily Mail Reporter, 2009) and has seen icing events two times since then. The first was in February 2009 when the bridge had to be closed due to ice shedding and damaging several vehicles (Daily Mail Reporter, 2009). Although the transport authorities took a public lashing, they found it “unusual” and left it at that. However, the bridge experienced another icing event in December of 2009 that required lane closures ("Severn bridges, hit by ice falls, reopen after closures", 2009). There has been a total of 12 claims for damages to vehicles due to ice shedding in 2009 ("Compensation claims after Severn bridge ice closures", 2010), which prompted engineers and the transport authority to look for answers from experts around the world. They have considered using a coating technology, however, it has been felt that the
frequency of events does not warrant the expense of coating all of the above deck structure (WalesOnline, 2009).

1.2.6 Uddevalla Bridge

The Uddevalla Bridge is located in Uddevalla, Sweden that crosses the Sunninge sound (Uddevalla Bridge in Sweden, 2012). This bridge was opened to traffic in 2000 and has been experiencing frequent icing problems ever since (Bowers, 2014). Pulse electro-thermal de-icing (PETD) has been deployed on one cable and one pylon of the bridge for testing. Field testing, though successful, revealed a mechanical design flaw (Petrenko, Sullivan, Kozlyuk, Petrenko, & Veerasamy, 2011). Two additional technologies were investigated, which included internal heating and water repellant paint. After thorough investigation, no technology was deemed field ready, and therefore, was deployed onto the bridge. However, a monitoring system was implemented to provide early warning and continuous event monitoring.

1.3 Objectives

There are three main objectives achieved in this thesis. The first is to update the case study of the Veterans’ Glass City Skyway (VGCS) with the most recent weather event. This event occurred in January of 2015 and will be documented for the first time in this thesis. Although this event only generated roughly 1/8 of an inch of ice accumulation, it caused the VGCS to close all northbound travelling lanes for approximately 8 hours. This event did have ice shedding that is considered unusual
because the threshold for ice fall was believed to be 1/4 of an inch. The icing event is fully documented in Chapter 3.

The second major objective is to document the evaluation and sensor development performed by the University of Toledo icing research team. There is information regarding stay sheath condition that is critical for improving the way icing and wet snow events are handled. The information relates to the thickness of ice/wet snow accumulations as well as the presence and state of water on the stay sheaths. The data will ultimately improve the real time monitoring system’s accuracy allowing for better decisions to be made by operations personnel. Additionally, gaining this information may eliminate on-site visits. On-site visits are dangerous considering they put operations personnel in harm’s way during harsh winter weather conditions.

The sensor evaluation considers several commercially available sensors that can determine ice presence, thickness, and even the state of water. However, the sensors that are commercially available can be awkward to install on the bridge due to how they need to be mounted or misrepresent stay sheath conditions. Therefore, the University of Toledo research team has designed and developed both an optical sensor and a presence and state sensor. The optical sensor can determine the thickness of ice or wet snow accumulation. The presence and state sensor is a contact sensor that determines the presence and state of water on the sheath.

The third objective is to discuss the ice accumulation and shedding experiments performed at the University of Toledo’s Scott Park Campus where the outdoor field experiment station is located. Initially these experiments were performed in order to expose the University of Toledo Presence and State Sensor to weather cycles. However,
there has been valuable observations pertaining to ice shedding on stainless steel cable-stay sheaths that are discussed. These observations open the door to the potential of a shedding model to be created in the near future. This shedding model could potentially predict a small time window of when ice shedding would occur, e.g. 45 minutes – 2 hours. This would allow operations personnel to make decisions more efficiently by deploying traffic control techniques only when needed, thus, allowing for less of a disturbance to the travelling public.

1.4 Organization of Thesis

Chapter 1 introduces the problem of icing and wet snow accumulation on bridges with above deck structure. This chapter also provides insight on how cable-stayed bridges that have experienced such events handled the problem. Chapter 2 presents a case study regarding icing on stainless steel cable sheaths. This case study provides the background and reasoning of the sensors developed to improve the monitoring of weather events, understanding of shedding, and applied administrative strategy. Chapter 3 presents the January 2015 icing event that occurred on the Veterans’ Glass City Skyway. This icing event offers new insight on ice shedding from the stainless steel sheaths and is documented for the first time in this thesis. Chapter 4 discusses the evaluation and sensor development that the University of Toledo icing research team has completed. This chapter takes an in-depth look into the data collection of two unknown variables that pertain to cable-stay sheath conditions throughout an icing or wet snow event. The two pursued variables are the thickness of accumulation as well as the presence and state of water on the stay sheath. Additionally, there have been several ice accumulation and
shedding experiments that have been performed throughout the winter of 2014 – 2015 that are presented in this chapter. These experiments resulted in valuable observations regarding icing events and motivate a shedding model. Chapter 5 provides a conclusion and recommendations to future work.
Chapter 2

Icing on Stainless Steel Sheaths

2.1 General Bridge Background

The Veterans’ Glass City Skyway (VGCS), formerly known as the Maumee River Crossing, is a large cable-stayed bridge on Interstate 280 that crosses over the Maumee River in Toledo, Ohio. At the time of its construction, the VGCS was known as the largest project to ever be carried out by the Ohio Department of Transportation (ODOT). The design began in April of 1999 and the bridge was officially opened to traffic in June of 2007 (“The Veterans’ Glass City Skyway”, 2015). The project consisted of 7,575-feet of approaches and a main span that is 1,225-feet in length. The main span, seen in Figure 2-1 on the following page, has a single central pylon that rises 216 feet above the bridge deck and a single plane of stays. The VGCS carries three lanes of traffic in each direction and has approximately 53,660 vehicles crossing daily (D. Foukes, personal communication, April 27, 2015).
The VGCS has numerous innovative features, which include: the cradle system for the stays, the stainless steel cable-stay sheaths, and the illuminated pylon. The VGCS utilizes a new cradle system that eliminates the need for cable anchorage in the pylon by allowing the stays to extend from one side of the bridge deck to the other. This ultimately permits the tower to be more slender (Nims, 2014). In addition to the cradle system, the VGCS cable-stay sheaths are unique due to the material that was chosen. Brushed stainless steel was selected for the sheaths rather than the typical HDPE material due to the low life cycle costs as well as aesthetic purposes. Some characteristics of the stay sheaths include being made of 1/8 inch thick 316L stainless steel, a brushed finish, and a larger than typical diameter. The reflection of light off of the stainless steel sheaths gives a unique appearance and enhances the illuminated pylon’s effect. The illuminated pylon uses internal LED lighting and has infinitely variable light schemes; one of which can be seen in Figure 2-2 on the following page.
2.2 Problem Statement

Since the VGCS has opened, there have been six major icing events that have led to damaged vehicles and/or lane closure on the bridge. In 5 of the 6 past events, ice accumulations have exceeded 1/4 inch and persisted on the stay sheaths for durations of time that range from several days to more than 10 days. When temperatures rise above freezing (32°F) and/or solar radiation reaches a critical level, ice shedding typically occurs, although other mechanisms can also cause shedding. Thick ice usually sheds in semi-cylindrical sheets and can be blown across several lanes of traffic depending on wind speeds. The complete shedding of a single stay can take place in less than a minute (Nims, 2014). The ice sheets can fall upwards of 200 feet to the roadway below creating damage to vehicles traveling the bridge. Typically, ODOT closes several lanes of traffic due to potential ice fall throughout an icing event. Currently, ice presence and thickness on the stay sheaths is determined only by reference to local weather data or nearby sensors and must be confirmed manually, putting ODOT personnel in harm’s way.
2.3 Historical Weather History

There have been five major historical icing events that have caused the VGCS to close lanes of traffic. The first four major icing events were reported by Kathleen Jones, Cold Regions Research and Engineering Laboratory expert and icing team member. The last icing event, February 2011, was captured and documented by the researchers from the University of Toledo and the University of Cincinnati. There are several different types of precipitation that can cause icing events, which include: rain, freezing rain, ice pellets (sleet), snow, or a combination of two or more types. Four of the five events that occurred on the VGCS were caused by freezing rain. Regional icing that affects the VGCS takes place as a result of the warm air from the Gulf of Mexico rising over the cold air coming from Canada. This weather pattern leads to the formation of supercooled liquid droplets from precipitation that originates in the warm air layer, which are likely to freeze when impacting a cold surface. These supercooled liquid droplets freeze on impact because of convective and evaporative cooling, with some contribution from super cooling, thus, starting ice accretion.

2.3.1 December 2007

The VGCS experienced its first major icing event shortly after opening to traffic. In December of 2007, ice accumulation went unnoticed until shedding occurred. Since the ice accumulation was not observed, data had to be reviewed and studied to determine the likely source of the accumulation. The data that was used came from the Toledo Express Airport and Metcalf Field (Toledo Executive Airport). It indicated that there was freezing rain and fog that occurred on December 9 – 10, which are believed to be the
cause of ice accretion for this event. The combination of rising ambient air temperatures and rainfall triggered the shedding event on December 12. Ice shedding resulted in both damaged vehicles and the closure of the two inside southbound travelling lanes, the lane closest to the median and the center lane (Jones, 2010).

2.3.2 March 2008

The second icing event that the VGCS experienced occurred just a few months later in March 2008. Once again, the ice accumulation was not observed so weather data from both the Toledo Express Airport and Metcalf Field was utilized to determine the cause. The weather data indicated that a snow and rain event associated with temperatures below freezing and a concurrent fog took place on March 27. This event is believed to have caused the cable-stay sheaths of the VGCS to accrete ice. The following afternoon, March 28, ice shedding occurred due to clear skies (intense solar radiation) and ambient air temperatures above freezing. During the shedding event, ODOT had to close the two inside lanes in each direction and at least one vehicle was damaged (Jones, 2010).

2.3.3 December 2008

In the third icing event on the VGCS, the ice was observed on the stay sheaths the day following the accumulation process. The ice accumulation was a result of freezing rain, snow and fog that occurred on two separate occasions according to data gathered from Toledo Express Airport and Metcalf Field as well as articles from the Toledo Blade. The snow accompanied by fog occurred on December 17 and the freezing rain took place on December 19. Ice then persisted until December 24 when the conditions for shedding
were met. The shedding event was triggered by rising ambient air temperatures and gusty winds. During the shedding event, ODOT closed the two inside lanes in both directions. There were not any reports of vehicle damages (Jones, 2010).

2.3.4 January 2009

In January 2009, the VGCS experienced its fourth major icing event. Weather data from the Toledo Express Airport and Metcalf Field as well as articles from the Toledo Blade showed that the most likely cause of ice accumulation was freezing rain accompanied by fog. Once on the stays, ice persisted from January 4 to January 13. Ice shedding was triggered by a combination of gusty winds and rising ambient air temperatures on January 13. Throughout the ice persistence and shedding, ODOT closed the inside lane in each direction. Lanes remained closed until January 21. This is believed to be due to the persistence of ice on the VGCS’s central pylon. There were not any reports of vehicles damaged in this event (Jones, 2010).

2.3.5 February 2011

The fifth icing event to cause lane closures on the VGCS occurred in February 2011. This was the first icing event to be documented in detail from the start of ice accumulation to the time ice shedding occurred. The cause of ice accumulation was freezing rain that started during the night of February 20. In this event, the icing research team observed ice accumulations exceeding a 1/2”. The ice then persisted throughout the day on February 21 without incident. Although the ambient air temperature was below freezing on February 22, there was water present in the interstice between the stay sheath and ice layer. The presence of water was caused by intense solar radiation and was
deemed a precursor to imminent shedding. This phenomena prompted ODOT to close the inside lanes in both directions. However, the ice did not shed and the water in the interstice refroze at night. The ice then persisted until 8:40am on February 24, which is when the shedding event caused by rising ambient air temperatures and solar radiation began. Around 9:30am traffic had to be stopped due to large pieces of ice falling dangerously close to vehicles in the outer lane. The main ice fall continued until 11am. There were not any reports of vehicles damaged during the shedding event. For a full detailed report of this icing event see Belknap (2011) and Nims (2014).

2.3.6 Lessons Learned from Historical Icing Events

Several lessons can be learned from studying the VGCS’s icing event history. The first lesson is the mechanism of ice accretion on the stay sheaths. In all five events, freezing rain and/or snow associated with fog and ambient air temperatures below freezing were the conditions that allowed for ice accretion. Additionally, it has been observed that minimal precipitation can cause significant amounts of ice accumulation on the stays. This is likely to be possible because some of the ice which accretes on the stay sheath is from super-cooled drizzle or cloud droplets (Jones, 2010). Secondly, shedding typically occurs when ambient air temperatures rise to above freezing and is accompanied by gusty winds, significant solar radiation and/or rain. A major observation that was made from the February 2011 event was that the ambient air temperature does not necessarily need to be above freezing in order for an ice shedding event to occur. This is due to the “greenhouse effect” in the interstice between the ice layer and the sheath surface. This effect is caused by intense solar radiation considerably increasing the stay sheath temperatures, thus, heating the ice-build up through conduction. In the February
2011 event, a considerable amount of water flowed in the interstice even though the ambient air temperature was in the mid-20’s degrees Fahrenheit.

2.4 Technology Matrix and Technology Selection

Initially, ODOT was seeking an active or passive technology that would solve the VGCS icing problem. An active technology is one that can be activated (powered on) and used only when needed whereas a passive technology is one that is constantly available and does not need to be activated (powered on) (Nims, 2014). Although icing on cable-stayed bridges is more common than originally thought, there is not an out-of-box solution that can be implemented. Literature regarding all known types of anti/de-icing technologies that have been previously applied to industrial facilities, bridges, and other structure located in cold climates was reviewed. Details regarding the literature review can be found in Arbabzadegan (2013) and Nims (2014). After literature was reviewed, the technologies were assessed and selected by the research team based on efficiency, costs, and environmental friendliness. Technologies that were selected were then tested in field experiments as described in detail in Section 2.6.

Through literature review, 80+ potential active or passive technologies were identified and classified into 13 different categories forming the technology matrix. This technology matrix includes a description of each technology, a discussion of its advantages and disadvantages pertaining to the VGCS, its implementation readiness level, and status of each technology (Belknap, 2011; Arbabzadegan, 2013). Further details regarding the technology matrix can be found in Nims (2010). The technology breakdown in terms of categories is as follows:
1. Chemical and chemical distribution
2. Coatings
3. Modifying the stay design to prevent ice accumulation
4. Electro-expulsive electrical de-icing systems
5. Pneumatic expulsive de-icing systems
6. Hot air
7. Infrared radiant heat
8. Heating the ice-substrate interface
9. High-velocity water, air, or steam
10. Manual deicing methods
11. Piezoelectric
12. Vibration or covers
13. Ice detection

The research team worked along with ODOT representatives to narrow down the 80+ technologies in order to find an appropriate solution to the icing problem that was frequently occurring on the VGCS. The technologies were eventually narrowed down to several that were deemed viable. There were five different technologies to be considered from three categories, which can be seen in Table 2.1. The technologies were then tested on either 10 foot VGCS stay sheath specimens at the outdoor experiment station or a small scale stainless steel specimen in the icing tunnel.
Table 2.1: Technologies to be Tested

<table>
<thead>
<tr>
<th>Category</th>
<th>Technology Under Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals</td>
<td>Beet Heat</td>
</tr>
<tr>
<td>Coating</td>
<td>Hydrobead</td>
</tr>
<tr>
<td></td>
<td>Phase Break TP</td>
</tr>
<tr>
<td></td>
<td>Boyd WeatherTITE</td>
</tr>
<tr>
<td>Heat</td>
<td>Internal</td>
</tr>
</tbody>
</table>

2.5 University of Toledo Testing Facilities

In order to evaluate the technologies that were deemed viable, an icing tunnel and a field experiment station had to be designed and built. The icing tunnel allowed for coating technology to be assessed through lab experiments on small scale specimens. The field experiment station permitted chemical, coating and heating technologies to be evaluated in field experiments on 10-foot VGCS stay sheath specimens. The icing tunnel is located on the University of Toledo’s Engineering Campus and the field experiment station is located at the University of Toledo’s Scott Park Campus.

2.5.1 The University of Toledo’s Icing Tunnel

The icing tunnel was designed and built by University of Toledo masters student, David Whitacre. This particular facility is primarily used for icing research pertaining to wind turbines. The icing tunnel consists of several subsections, which include: a test section, freezing room, and closed loop tunnel system as illustrated in Figure 2-3. The walls of the icing tunnel are insulated in order to reduce temperature gains and allow the
closed system to maintain a constant temperature. Additionally, the icing tunnel allows for different weather conditions to be simulated due to being able to adjust wind speeds and temperatures. The adjusting of these variables makes it possible to simulate an icing event similar to one that the VGCS experiences.

Figure 2-3: University of Toledo Icing Tunnel SolidWorks Design (Whitacre, 2013)

Figure 2-4: The University of Toledo Icing Tunnel (Likitkumchorn, 2014)

The test section of the icing tunnel consists of a 12 inch diameter clear tube, a specimen mounting system, a misting system, and a camera as seen in Figure 2-5. The 12 inch diameter clear tube allows for the operator to be able to view the specimen as
well as take photos easily throughout an experiment. The mounting system allows for testing specimens to be easily situated in the test section area of the icing tunnel. The misting system seen in Figure 2-5 is capable of creating both rime and glaze ice types (Likitkumchorn, 2014). As seen in Figure 2-6, the misting system is set up roughly 12 inches in front of the test specimen in order to allow the wind to carry small water droplets an appropriate distance to resemble field icing conditions (Likitkumchorn, 2014). This system is hooked up to city water through a water tap located in the laboratory. The misting system also has interchangeable nozzles allowing for various water droplet sizes to be used in an icing experiment. Also seen in Figure 2-5 is a camera. This camera is located in the test section in order to allow the user to take videos of the entire experiment.

![Camera and Misting System](image)

*Figure 2-5: Misting System and Camera in Test Section (Likitkumchorn, 2014)*
Further details regarding the UT icing tunnel can be found in Whitacre (2013).

2.5.2 The University of Toledo’s Field Experiment Station

As previously mentioned, every technology that was deemed plausible for implementation was field tested. In order to field test several technologies, an outdoor field experiment station had to be created considering testing on the bridge would be dangerous under winter conditions. Additionally, an outdoor testing facility allows for icing events to be simulated rather than waiting on a natural occurrence; for example, icing can be initiated by spraying water if there is no natural precipitation. The field station was set up on a concrete pad located behind one of the buildings at the University of Toledo’s Scott Park Campus. The field station consists of three 10 foot long full scale VGCS specimens. The specimens have the same diameter, material, and reflective brushed surface as the VGCS’s cable-stay sheaths. Displayed in Figure 2-7 and 2-8 below is an overhead view of the field station and the setup of the full scale specimens.
Figure 2-7: Overhead View of Outdoor Field Experiment Station (Nims, 2014)

Figure 2-8: Stay Sheath Orientation and Angle during Experiments (Nims, 2014)

As seen in Figure 2-8, two of the full scale specimens are positioned at approximately 26° angles and the third is laid on its side (0°). The researchers chose a 26° angle for the two stay sheaths due to it being the shallowest angle used on the VGCS. The shallowest angle is believed to be the worst angle when it comes to ice accretion. This is due to the fact that ice accretion is a slow process and because of the likelihood that water would run down a steep stay sheath rather than contribute to ice accumulation. The stay sheath that was laid on its side was done in order to simulate the worst possible ice accumulation case, which is 0°. This particular case would allow for the maximum
ice accretion rate to be achieved due to minimal water running off the sheath. Additionally, the stay sheaths were positioned north to south to simulate the stay orientation of the VGCS.

2.6 Experiments & Results

Experiments performed at the field station consisted of accumulating and shedding ice. Throughout the experiments, several technologies were used either as an active anti/de-icing technology or a passive anti/de-icing technology. The technologies investigated on the full scale specimens include the following: coating used as an anti-icing technology, thermal used as both an anti-icing and de-icing technology, and chemical used as both an anti-icing and de-icing technology. Additionally, there were numerous experiments performed in the UT icing tunnel utilizing the misting system to accrete ice. The experiments investigated three different types of coating applied to small scale specimens as an anti-icing technology.

During the outdoor field station experiments, the specimens had a wide variety of sensors implemented on them, which included thermistors, an array of photosensors, and an array of prototype UT Presence and State Sensors. The thermistors were used to track the temperature changes that the surface of the stay sheath specimen underwent. The array of photosensors was used to track the sun location and solar radiation effects. The UT Presence and State Sensor array, which consists of flat thermocouples and sensing terminals, was used in order to determine the presence and state of water as well as temperatures at individual locations on the stay sheath. In addition to the stay sheath sensors, there was a local weather station on-site that provided ambient temperature, wind
speed, and wind direction at the field station throughout experiments (Arbabzadegan, 2013).

2.6.1 Ice Accumulation and Shedding Experiments

In order to understand the icing problem that was frequently occurring on the VGCS, ice accretion and shedding experiments were performed. These particular experiments were conducted at the field experiment station. The experiments were done throughout a cold night where temperatures were below freezing (32°F). The process takes between 4-10 hours depending on the temperature outside and the thickness of ice accumulation desired, e.g. 1/4 inch of ice accumulation at 26°F-29°F takes roughly 4-5 hours. The best period of time to do an entire experiment, accumulation and shedding, is when temperature is below freezing throughout the night and above freezing the following day. If studying ice persistence and/or solar radiation effects is desired, proper weather conditions are below freezing for several days and nights as well as a clear sky during the daytime periods.

The most critical part of an icing event is the shedding of ice accumulation from the stay sheaths. Shedding can occur in several ways, which include: ambient temperature being above freezing, clear skies (solar radiation), or a combination of both. These conditions have been shedding triggers in past events on the VGCS (Jones, 2010; Arbabzadegan, 2013; Belknap 2011; Nims, 2014). A more detailed description of shedding conditions that have been simulated in the winter of 2014-2015 along with several observations that open the door to the investigation of a shedding model for icing on stainless steel will be presented in Chapters 3 and 4.
A common set up for ice accumulation and shedding experiments can be seen in Figure 2-9 below. The ladder is used to hold the hose and spraying nozzle in place throughout an experiment. A common placement for the hose is several feet away from the stay sheath depending on the wind. Additionally, the hose should be upwind from the stay sheath in order to allow the cold wind gust to blow the water droplets onto the stay sheath. The setup allows for fine mist to hit the stay sheath and instantaneously freeze. Large water droplets will melt built-up ice layers on the stay sheath due to latent heat and the fact that the water discharged from the hose is roughly 34°F (Nims, 2010).

Figure 2-9: Typical Ice Accumulation Setup (Nims, 2014)

Once ice accumulations of desired thickness were met, they were allowed to persist until one of the shedding conditions mentioned above occurred. This typically happened the following day due to when the experiments were carried out. Shedding experiments allow for knowledge of how the stainless steel and ice layers react to increasing temperatures and/or solar radiation. Several observations have been made that verify those seen on the bridge. For instance, solar radiation and rising temperatures create a presence of water within the interstice between the stay sheath and the ice layer (Figure 2-10), solar radiation creates a significant increase in temperature of the stainless
steel sheath, ice thickness typically needs to be above the 1/4 inch threshold in order to shed, and ice sheds in curved sheets. Further details regarding the correlation between stay sheath temperatures and shedding for the winter experiments prior to the 2014-2015 winter can be found in Arbabzadegan (2013), Likitkumchorn (2014), and Nims (2014).

Figure 2-10: Water in the Interstice between the Sheath and Ice Layer (Nims, 2014)

2.6.2 Coating Experiments

2.6.2.1 University of Toledo Icing Tunnel Coating Experiments

Coating experiments were performed in the UT icing tunnel. By using the icing tunnel, the weather conditions could be simulated and controlled, thus, allowing for the same conditions to be used for all experiments. Using the same conditions allows for appropriate observations when it comes to comparing the different coatings with each other and an uncoated specimen. The conditions that were set mimicked a typical freezing rain storm, which was a temperature of 22°F and a wind speed of roughly 29 fps (Likitkumchorn, 2014). Once the icing tunnel’s internal temperature stabilized, specimens were placed into the test section and the misting system was turned on to simulate precipitation. Three coatings were evaluated using several different nozzle
sizes. The coatings that were evaluated included Hydro bead, Phase Break TP, and Boyd WeatherTITE. The nozzle size was varied in order to determine whether the droplet size had any effect on the success of the coatings. All experiments lasted 10 minutes. Results from the experiment may be seen in Table 2.2.

<table>
<thead>
<tr>
<th>Coating Droplet Size</th>
<th>Uncoated in.</th>
<th>Hydrobead in.</th>
<th>PhaseBreak TP in.</th>
<th>WeatherTITE in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 micron</td>
<td>0.256</td>
<td>0.394</td>
<td>0.394</td>
<td>0.315</td>
</tr>
<tr>
<td>42 micron</td>
<td>0.217</td>
<td>0.256</td>
<td>0.256</td>
<td>0.374</td>
</tr>
<tr>
<td>50 micron</td>
<td>0.197</td>
<td>0.256</td>
<td>0.217</td>
<td>0.374</td>
</tr>
</tbody>
</table>

As it can be seen in Table 2.2, all three coatings were ineffective regardless of the droplet size. Furthermore, the coatings slightly increased the thickness of accreted ice on the specimen in every instance. This is more than likely due to the difference in ice structure that the coatings created. There were two ice layer structures that were observed during these experiments regardless of the droplet size used. The first icing structure for the uncoated specimen consisted of water droplets which formed puddles that increased until they covered the entire specimen and froze as a single layer as seen in Figures 2-11, 2-12, and 2-13. The second icing structure that was observed was typical for all coatings evaluated. During the experiments where the three coatings were applied, the coatings began to work by not allowing the water to instantaneously freeze. However, the water droplets did not roll off of the specimen due to gravity or wind, but rather began to freeze in place. Due to the individual droplets freezing in place rather than collecting into puddles, the first ice layer had an uneven surface. The uneven surface trapped water and allowed ice to accumulate more rapidly. This icing structure process can be seen in Figures 2-14, 2-15 and 2-16. These particular figures are from the
Hydrobead experiment, however, the observations that can be made from them are representative of all coatings that were evaluated.

Figure 2-11: Formation of Water Puddles – Uncoated (Likitkumchorn, 2014)

Figure 2-12: Formation of Ice Layer – Uncoated (Likitkumchorn, 2014)

Figure 2-13: Specimen at Conclusion of Test – Uncoated (Likitkumchorn, 2014)
Figure 2-14: Individual Water Droplets Beginning to Freeze, Typical for Coated Specimens (Likitkumchorn, 2014)

Figure 2-15: Uneven Ice Layer, Typical for Coated Specimens (Likitkumchorn, 2014)

Figure 2-16: Specimen at Conclusion of Test, Typical for Coated Specimens (Likitkumchorn, 2014)

For further details please refer to Nims (2014) and Likitkumchorn (2014) where images for each coating throughout the icing experiment can be found.
2.6.2.2 Field Station Coating Experiments

Hydrobead was selected for the outdoor full scale experiment because of its potential to make materials water repellant and ice phobic. For this experiment, the specimen that was laid flat on its side was used in order to study whether a coating could repel water and stop ice build-up in the worst case scenario. The specimen was instrumented using flat thermocouples in order to study the thermal behavior of the stainless steel sheath throughout the experiment when a coating was implemented (Nims, 2014). Using a manual sprayer, Hydrobead was misted onto half of the specimen as seen in Figure 2-17. This was done so that the research team could compare the use of a coating applied to a stainless steel sheath to a stainless steel sheath without a coating with the same characteristics and setup.

![Experimental Setup](image)

Figure 2-17: Experimental Setup (Arbabzadegan, 2014)

Water was then misted onto the entire specimen in a similar manner as shown in Figure 2-9. As with the UT icing tunnel experiments, the coating was initially effective by not allowing the water to instantaneously freeze to the VGCS test specimen. However, the water droplets did not roll or blow off of the specimen, but rather froze in
place as seen in Figure 2-18. Although the coating slowed down the ice build-up rate initially, it changed the structure of the ice similarly to what was observed in the icing tunnel experiments and did not stop ice accumulation from occurring. When combing its ineffectiveness and long term durability concerns, the anti-icing technology was deemed inadequate for the VGCS icing problem.

![Figure 2-18: Frozen Droplets over the Coating (Arbabzadegan, 2013)](image)

For further details regarding the outdoor coating experiments, please refer to Arbabzadegan (2013) and Nims (2014).

### 2.6.3 Thermal Experiments

The VGCS stay sheaths are large in diameter, 18 to 20 inches, for aesthetic purposes and roughly half of the inside volume is hollow as seen in Figure 2-19. Inside the VGCS stay sheaths, there are 82-156 epoxy coated strands depending on the location of the stay on the bridge. Thus, internal heating used as a thermal anti/de-icing technique was deemed plausible. Therefore, two outdoor experiments at the field station were
performed in order to determine whether heating would be effective for anti-icing or de-icing.

The experiment was setup by placing approximately 120 strands into the sheath, instrumenting the sheath with flat thermocouples to collect temperature data at three points, and setting up a 70,000 BTU forced air space heater. The strands were placed at the bottom of the sheath for the experiment. Although the strands are at the top of the cross-section at mid height on the bridge, this was considered thermally acceptable because the conduction of heat through the stainless steel sheath is more significant than the convection of heat to the strands inside the sheath (Nims, 2014; Arbabzadegan, 2013). An anemometer that collected air speed and temperature of the pipe’s inlet and outlet was used in combination with thermocouples that were installed at the bottom, middle, and top of the specimen in order to determine the thermal effects of the sheath. The experimental setup can be seen in Figure 2-20 below.

Figure 2-19: VGCS Stay Sheath Cross-Section (Arbabzadegan, 2013)
Figure 2-20: Thermal Experiment Setup (Arbabzadegan, 2013)

Two experiments to determine the effectiveness of internal heating were performed. In the de-icing experiment, the research team accumulated a 1/2 inch thick ice layer on the sheath and then blew hot air generated by the 70,000 BTU heat source into the open portion of the stay sheath’s cross-section until the ice was completely removed. The thermal de-icing technique was able to successfully remove the ice layer without shedding; otherwise, the ice layer melted in place. Figure 2-21 illustrates how the ice melted off the sheath.
In the anti-icing experiment, the specimen was first heated to a temperature above freezing. The idea was to maintain a temperature above freezing throughout the entire experiment while water was misted onto the sheath in order to prevent ice accumulation. However, it was observed that ice began to accumulate onto the sheath after a short period of time. Therefore, the sheath temperature couldn’t be maintained, which ultimately allowed ice to accumulate. The accumulation of ice can be seen in Figure 2-22 below.
In conclusion, it was determined that internal heating used as a de-icing technique is effective, however, it is ineffective when used as an anti-icing technique. Though the de-icing technique proved to be successful, the installation of heaters for each stay would be cost ineffective. Thus, the research team deemed this particular technology to be impractical and ruled it out as solution to the icing problem that the VGCS is experiencing. For further details regarding the outdoor thermal experiments, please refer to Arbazadegan (2013) and Nims (2014).

### 2.6.4 Chemical Experiments at the Field Station

The last technology that was evaluated at the outdoor experiment station was chemicals. The experiments were performed in order to determine not just if the chemicals were a suitable solution to the VGCS icing problem, but whether they would have a negative effect to the aesthetics of the stainless steel sheath as well. The chemical used throughout these experiments is Beet Heat. Beet Heat is an organic fluid that consists of refined molasses carbohydrate, NaCl, CaCl2, KCl, and MgCl2.
Beet Heat was used in two separate experiments; in one it was utilized as a de-icing strategy and in the other it was used as an anti-icing method.

In the de-icing experiment, the research team accumulated a 1/8 inch thick layer of ice. Once the ice was accumulated, Beet Heat was applied through a drip tube system. Unfortunately, it was observed that Beet Heat did not remove the thin layer of ice, but rather melted narrow rivulets through the ice. This was theorized to be due to the low viscosity of the chemical (Arbabzadegan, 2013; Nims, 2014). Figure 2-23 shows how the Beet Heat melted narrow rivulets in the ice layer.

![Figure 2-23: Chemical De-icing Pattern (Arbabzadegan, 2013)](image)

In the anti-icing experiment utilizing Beet Heat, the fluid was first applied by using a manual sprayer to mist Beet Heat onto half of the specimen. Once the chemical was applied, the research team began the accumulation process by misting water onto the specimen. The results were similar to the coating experiment. The chemical would slow down the freezing process by not allowing the fine water mist to instantaneously freeze.
on impact with the stay sheath. However, the water would not roll off or down the specimen, but rather begin to freeze as seen in Figure 2-24. Through experimentation, the chemicals proved to be ineffective in terms of performance. Therefore, they were ruled out as a potential technology to be implemented on the VGCS.

![Image of anti-icing chemical experiment](image)

**Figure 2-24: Icing Pattern for Anti-Icing Chemical Experiment (Arbabzadegan, 2013)**

For further details regarding the outdoor chemical experiments, please refer to Arbazadehgan (2013) and Nims (2014).

### 2.6.5 Summary of Experiments

In conclusion, no existing active or passive anti/de-icing technology was found to be efficient in terms of performance and/or cost effectiveness, and therefore, ODOT chose to pursue event monitoring and traffic control. Although an administrative strategy will not prevent or remove ice accumulation on the cable-stay sheaths, it will allow ODOT to keep the travelling public safe. In order to have an accurate and efficient administrative strategy, it was determined that a real time monitoring and assessment system needed to be designed and developed. The goals of the monitoring system are as
follows: 1.) to make ODOT aware of ice accumulation without having to go on-site to check, 2.) to notify ODOT that ice fall is likely to occur, and 3.) to help ODOT make traffic control decisions in both a timely and cost effective manner. To achieve these goals, the local and microclimate of the VGCS were needed.

2.7 Instrumentation of the Veterans’ Glass City Skyway

As previously mentioned, ODOT elected to pursue an administrative strategy, which ultimately required the design and deployment of a real time monitoring system. For this monitoring system to be accurate, the local climate as well as the VGCS’s microclimate needed to be known throughout an icing event. Data regarding the local climate was obtained from the ODOT Road Weather Information System (RWIS) and several local airports. The RWIS station nearest the VGCS consists of the following sensors: Linux RPU – RWIS Elite Weather Station Platform, Wireless Pavement Sensor X6, RM Young Ultrasonic Wind Sensor, RM Young Air Temperature and Dew Point Sensor, and Weather Identifier and Visibility Sensor. The local airports used for harvesting local weather data such as ambient air temperature, dew point, wind speed and direction, cloud cover and heights, visibility, barometric pressure, precipitation amount, and lightning are the Toledo Express Airport and Toledo Executive Airport (Agrawal, 2011). Although the existing sources for weather data contained valuable information, the data is limited to the local weather surrounding the VGCS rather than the data pertaining to the specific microclimate and stay sheath condition. Furthermore, to improve the real time monitoring systems accuracy, the existing sensor array located on
the bridge needed to be upgraded to capture data pertaining to the microclimate of the bridge and the condition of the stay sheaths.

To improve data collection and the accuracy of the real time monitoring system, the VGCS needed to be instrumented with several sensors that could provide data that was lacking. The lacking data mainly pertained to the condition of the stay sheaths. The information that was needed included presence of ice, thickness of ice, stay sheath temperature, solar radiation, and precipitation on the bridge. Having access to this particular data will not only allow the monitoring system to be accurate and help ODOT make informed decisions regarding traffic control, but potentially eliminate on-site visits for manual thickness measurements and ice presence verification, thus, reducing the risk imposed on ODOT personnel. Table 2.3 lists the required information, reason it is required, and sensor that will provide the needed data.
Table 2.3: Uncertainties that Needed to be Resolved and Corresponding Sensors

<table>
<thead>
<tr>
<th>Required Information</th>
<th>Uncertainties that need to be resolved</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presence of Ice</td>
<td>It is difficult to be certain when ice accumulates on the stay sheaths except by field observation.</td>
<td>Goodrich Ice Detector/ UT Presence and State Sensor/ LWS</td>
</tr>
<tr>
<td>Thickness of Ice</td>
<td>It is difficult to know the thickness of ice on the stay sheaths except for manual measurements. Ice thickness plays a major role in shedding.</td>
<td>Goodrich Ice Detector/ UT Optical Sensor</td>
</tr>
<tr>
<td>Stay Sheath Temperature</td>
<td>The temperature of the VGCS stay sheaths during icing events is unknown. Stay sheath temperature is vital in the prediction of ice accumulation and shedding.</td>
<td>Thermistors/ Thermocouples</td>
</tr>
<tr>
<td>Solar Radiation</td>
<td>Solar radiation can cause the sheath surface temperatures to rise above freezing even when ambient air temperature is below freezing. This causes the presence of water and is considered a trigger for ice shedding.</td>
<td>Sunshine Sensor</td>
</tr>
<tr>
<td>Precipitation on the Bridge</td>
<td>Type and amount of precipitation need to be determined throughout an icing event. The type and the amount of precipitation is vital to ice accumulation thickness</td>
<td>LWS/ Rain Tipping Bucket</td>
</tr>
<tr>
<td>Visual records of icing conditions</td>
<td>Observation of the stays condition during icing events can be valuable and eliminate field visits.</td>
<td>Camera</td>
</tr>
</tbody>
</table>

The VGCS has been instrumented over several years and is still currently in the process. The first addition to the existing sensor array came in October of 2012 when thermistors were added on two stay sheaths. Thermistors allow the surface temperature of the stainless steel sheaths to be known throughout an entire icing event, which is vital in the understanding of ice accretion and shedding. The thermistors were installed on stay 18 (span 27) and stay 8 (span 28) (Arbabzadegan, 2013). The locations of the thermistor arrays can be seen in Figure 2-25 below.
The second addition to the existing sensor array came in the summer of 2013 when the ROHN self-supporting tower was designed and built. The location is on the south side of the bridge and east side of the plane of stays as seen in Figure 2-26. The instrumentation tower supports several sensors listed in Table 2.3 above; which include the Goodrich Ice Detector, the Leaf Wetness Sensor, the Sunshine sensor, the Electrically Heated Rain and Snow Sensor, and a weather proof camera. These sensors provide vital information pertaining to the microclimate of the bridge, which ultimately allows for the breakdown and understanding of the icing events that frequently occur on the VGCS. For more information regarding these particular sensors, please refer to Deb (2013), Arbabzadegan (2013) and Nims (2014).
Although many of the voids in required weather data have been filled, there is still the issue regarding the condition of the stay sheaths. The sensors located on the weather tower provide useful information regarding the microclimate on the bridge, but they do not directly answer the questions of 1.) Is there ice on the stay sheath? and 2.) How thick is the ice on the stay sheath?. These are critical questions that need to be answered in order to provide the most efficient and effective monitoring system possible. The Goodrich Ice Detector is only so useful for ice presence and thickness as will be further discussed in the following chapter. An investigation into commercial sensors that can be mounted directly on the stay sheath or mounted on the tower and directed toward the stay in order to determine ice presence and thickness on the stay sheath itself has proven that no such sensor exists. Thus, sensors that can directly measure thickness as well as presence and state of water on a stay sheath have been designed, developed, and deemed deployable. The sensors that will be deployed in the summer of 2015 are the UT Presence and State Sensor and the UT Optical Sensor. The description, design and development will be discussed in the following chapter.
2.8 Real Time Weather Monitoring System

Information regarding the regional weather, microclimate on the bridge, and stay sheath condition is only efficient and effective when operations personnel acquire it in a clear and timely manner. The VGCS has been implemented with several sensors that allow the microclimate to be known. The data outputted from these sensors as well as the existing local weather sensors need to be integrated in a way that helps assist ODOT manage icing events. This was done by designing and developing a real time weather monitoring system referred to as the “dashboard.” The dashboard utilizes algorithms that are based on knowledge gained from previous icing events that occurred on the VGCS. The algorithms process weather data from several weather sources, which include: local airports, RWIS stations, and all the implemented sensors on the bridge. The dashboard is what ultimately gives bridge operations personnel an overall picture of the condition of the stay sheaths during an icing event.

The dashboard, seen in Figure 2-27 below, consists of several tabs that allow weather data to be analyzed in several ways. The tab labeled “dashboard” is the primary tab used during an icing event because it gives an overall picture of what is happening with the VGCS stays. This tab includes a speedometer-like indicator, a legend of the indicated state of transition, and a running history of the last 48 hours of recorded icing conditions. The dashboard processes weather data from the aforementioned sources in real time. Therefore, the algorithms that were developed from past icing events are used to process the data as it is happening, which ultimately allows the dashboard to shift states and give warnings regarding the likelihood that ice accumulation and shedding is occurring on the VGCS. Furthermore, a state of “Y1” is achieved if the icing
accumulation criterion set by the algorithm has been met for a minimum of one hour; a state of “Y2” is achieved if the icing accumulation criterion set by the algorithm has been met for a minimum six out of eight hours; and so on. After the criterion for accumulation has been met for ten hours, the dashboard requires ODOT to make an on-site visit to verify that icing has indeed occurred. There are two possibilities that can happen next, which are as follows: 1) a state of “Alert” is attained if ODOT verifies icing has occurred or 2) A state of “Clear” is achieved if ODOT verifies that icing has not occurred. Once a state of “Alert” occurs, the dashboard continues to process weather data to determine the probability of shedding. The transitioning of states occurs in the same manner as the transitioning of states for accumulation. The main difference is that the intervals are much shorter because ice shedding is a much quicker process when the proper conditions are met than ice accumulation.

The three other tabs included in the dashboard are as follows: 1) Map - Weather Data by Location, 2) History – access to recent past data from all sensors, and 3) Documentation. Please see Agrawal (2011), Deb (2013), and Nims (2014) for further information pertaining to the dashboard and its algorithms.
In conclusion, icing of bridges with above deck structure is a wide spread problem. Typically, a DOT or bridge owners and operators believe an off the shelf solution to these events exist. However, this is never the case due to the complexity of ice accumulation and shedding. There is only one known instance where active control is being utilize, which is cable collars on the Port Mann Bridge. This particular active control is possible with wet snow accumulation, but it is still in the early stages of implementation and has only been used with small accumulations. This technology is not possible with ice accumulation because the cable collars would simply slide over the ice. Additionally, this technology puts operations personnel at risk and requires manual attachment at the top of the stay sheaths.

An investigation into the icing events that occur on the VGCS has been performed. All known active and passive anti/de-icing technologies have been reviewed.
Coatings, internal heating, and chemicals were thought to be potential solutions. These particular technologies were both laboratory and field tested. The results from the anti/de-icing experiments did not show promise. The technologies investigated either failed to stop and/or prevent icing or were too costly. After all known technologies were deemed unworthy for bridge implementation, ODOT elected to pursue an administrative strategy.

To assist ODOT in fulfilling an efficient and effective administrative strategy, the icing research team instrumented the VGCS and designed and developed a real time weather monitoring system referred to as the “dashboard.” Instrumenting the bridge with sensors that provide weather data pertaining to the VGCS’s microclimate allows for the dashboard to relay accurate and reliable weather data to operations personnel in a timely manner. The dashboard is currently utilized by ODOT during the winter months. It has been proven effective and reliable in determining ice accumulation and shedding.

Although the microclimate on the bridge is known, variables relating to the condition of the stay sheaths need to be captured. As of now, the presence and state of water as well as thickness of ice on the stay sheath itself needs to be confirmed manually during on-site visits. This puts ODOT personnel in harm’s way during harsh winter weather conditions. Sensors have been designed and developed to capture this information.
Chapter 3

January 2015 Icing Event

3.1 Introduction

In January 2015, the VGCS experienced its first major icing event in four years. This event was documented by both ODOT and the researchers from the University of Toledo and the University of Cincinnati. ODOT made field visits every three hours in order to obtain data regarding ambient air temperature, current weather conditions, stay sheath temperatures and conditions, pylon temperatures and conditions, roadway conditions, and thickness of ice present on the sheaths; these observations can be found in Appendix A. The University of Toledo researchers made on-site field visits to the bridge on January 23 and 24 to take photographs and notes concerning ice persistence, ice shedding, and water presence on the stay sheaths. This particular event provides valuable insight into ice persistence and shedding. During the shedding event, a thin layer of ice releasing from the stay in small pieces was observed. This is the first time ice shedding of this fashion has been observed in either field experiments or on the bridge. Table 3.1 provides a summary of accretion triggers, shedding triggers, lane closures, and whether vehicles were damaged during shedding for all six events.
Table 3.1: Icing Event History

<table>
<thead>
<tr>
<th>Ice Event</th>
<th>Ice Accretion</th>
<th>Ice Shedding</th>
<th>Ice Persistence Duration (Days)</th>
<th>No. of Lanes Closed</th>
<th>Damaged Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 2007</td>
<td>Freezing rain and fog</td>
<td>Rain with temperature above freezing</td>
<td>2</td>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>March 2008</td>
<td>Snow, rain, and fog</td>
<td>Sun with temperature above freezing</td>
<td>1</td>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>December 2008</td>
<td>Snow and fog; freezing rain and fog</td>
<td>Rain, gusty winds and temperatures above freezing</td>
<td>7</td>
<td>2</td>
<td>No</td>
</tr>
<tr>
<td>January 2009</td>
<td>Freezing rain and fog</td>
<td>Gusty winds, temperature above freezing</td>
<td>10</td>
<td>1</td>
<td>No</td>
</tr>
<tr>
<td>February 2011</td>
<td>Freezing rain, clear</td>
<td>Light wind, overcast, and temperature above freezing</td>
<td>4</td>
<td>All</td>
<td>No</td>
</tr>
<tr>
<td>January 2015</td>
<td>Freezing rain and snow.</td>
<td>Gusty winds and overcast, remaining ice sublimated/melted of stays following day when ambient air temperature was above freezing</td>
<td>4</td>
<td>3 (NB)</td>
<td>No</td>
</tr>
</tbody>
</table>


3.2 Daily Description of the January 2015 Event

The most recent icing occurrence resulted in the closure of the Northbound travelling lanes. A light snow began around 3am and transitioned to a light freezing rain around 7:30am on January 21, 2015. By 10am, an ODOT shift supervisor recorded a measurement of 0.012 inches of ice accumulation on the VGCS’s stay sheaths. Freezing rain continued through the morning until it transitioned back to snow around 12:30pm. Additionally, the ambient air temperature stayed below freezing the entire day and peaked at 28°F around 5 pm. At 6:30 pm, two members of the University of Toledo icing research team along with a shift supervisor went to the bridge to take measurements and observe the accretion pattern. During this time, the ice accumulation was measured at roughly 1/8”. An example of the ice distribution can be seen in Figure 3-1 below.

![Figure 3-1: Distribution of Ice on January 21, 2015](image)

On January 22, the ambient air temperature stayed below freezing and the skies remained overcast as evident by Figure 3-2. The data for this figure came from the solar
sensor located on the bridge and was exported from the real time monitoring system. Figure 3-2 compares the global and diffuse radiation from the sun. It is possible to determine whether the skies are clear or not by comparing these particular values. When they overlap, the sky is overcast and vice versa. Furthermore, Figure 3-2 indicates that the solar radiation intensity was low during January 22 due to overcast skies throughout the day. Therefore, it can be concluded that the ice persisted because of below freezing ambient air temperatures and overcast skies.

**Figure 3-2: Global vs. Diffuse Radiation, January 22, 2015**

Although the skies were overcast for the majority of the day, solar radiation was still emitted. This warmed the stays causing the ice to partially melt. Also, ice was sublimated through the heat caused by the solar radiation. The melting of the ice caused the center of gravity to shift from the top to the east side, which ultimately allowed the ice to rotate slightly under its own weight. An example of the ice distribution caused by the weather on January 22, 2015 can be seen in Figure 3-3. Due to the potential of ice
fall, ODOT chose to close the inside (closest to the median) lane in the northbound direction.

![Figure 3-3: Distribution of Ice on January 22, 2015](image)

On January 23, 2015 before 10am, ODOT personnel saw some ice shedding from the stays. Although the ice accumulation was only 1/8” and vehicles likely would not have been damaged, ODOT felt that ice shedding would still be a safety concern due to ice hitting a vehicle being a distraction. The distracted driver then could cause an accident. Therefore, ODOT closed all northbound travelling lanes for the day beginning between 9 and 10am. Two members of the University of Toledo icing research team then returned to the bridge to make observations.
Although the ambient air temperatures were below freezing and the sky was overcast as evident by Figure 3-4, ice shedding occurred. The shedding was different than any event seen in either the field experiments or on the bridge. The thin layer of ice fell in fragments away rather than completely releasing from the stays in large sheets as had been seen previously. This effect may have been caused by the high winds that the bridge experienced. The pieces of ice that shed were small and thin as seen in Figure 3-5 (D). Most pieces of ice that shed were located in between the parapets and the inside shoulder of the northbound lanes. Figure 3-5 (B) shows white patches where the ice is separating from the stay sheath and Figure 3-5 (C) shows dark square patches where ice has shed from the sheath. Once it was clear the remaining ice was going to persist until the following day, ODOT opened up the right outer most northbound lane to traffic.
Figure 3-5: Photographs from January 23, 2015. (A) shows remaining ice accumulation on stays north of the pylon. (B) illustrates ice accumulation detaching on stays north of the pylon. The white patches seen in the photograph are where sections of ice accumulation are beginning to detach from the sheath. (C) portrays patches where ice shedding occurred on stays north of the pylon. (D) is a typical piece of ice that shed from the sheaths. All pieces that were measured were under 1/8”.

A threshold of 1/4” for ice shedding was previously identified through ice accumulation and shedding experiments (Nims, 2014). Typically, in experiments ice layers melt in place if ice accumulations are below this threshold. However, this was not the case on January 23 when temperatures were below freezing and solar radiation was not intense. Knowing that the temperatures were going to rise above freezing as the
weather forecast suggested and that shedding occurred in a unique way the day before, ODOT elected to leave the two inside (lane closest to the median and the center lane) northbound traffic lanes closed until either the ice completely shed or melted and ran down the stay sheaths. Additionally, an icing research team member returned to the bridge to make observations throughout the day.

As the ambient air temperature increased, water was present on the stays and the bridge deck. It was observed that the ice layer was diminishing and shedding was not occurring. By the end of the day, the majority of ice had melted in place and the resulting water ran down the stay sheaths. ODOT then opened all traffic lanes to the travelling public. Table 3.2 shows the lane closures throughout the icing event.

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of Lanes Closed</th>
<th>Starting of Lane Closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 21, 2015</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>January 22, 2015</td>
<td>1</td>
<td>Morning</td>
</tr>
<tr>
<td>January 22, 2015</td>
<td>2</td>
<td>Afternoon</td>
</tr>
<tr>
<td>January 23, 2015</td>
<td>3</td>
<td>Morning</td>
</tr>
<tr>
<td>January 23, 2015</td>
<td>2</td>
<td>Evening</td>
</tr>
<tr>
<td>January 24, 2015</td>
<td>0</td>
<td>Evening</td>
</tr>
</tbody>
</table>

3.3 Conclusion

There are two main observations that can be made from the January 2015 event. The way the ice layer shed from the stay sheaths in this event has never been observed during field experiments or icing events on the bridge. The first major observation that can be made is that shedding occurred when the ambient air temperatures were below
freezing and there was overcast skies. In the previous five events, the temperature was above freezing when shedding occurred, conversely, the ambient air temperatures remained below freezing during the January 2015 ice shedding event. The January 2011 event showed that ice shedding was possible with temperatures below freezing due to the greenhouse effect caused by solar radiation, however, the ice shedding that occurred during the January 2015 happened with overcast skies. It is believed that during the ice persistence, the solar radiation caused the ice to melt on the top of the stay sheath. This caused the center of gravity of the ice to shift towards the east. The gravitational force imposed on the ice by its own weight then allowed the ice to rotate slightly and separate from the stay sheath. Then on the following day, January 23, 2015, the wind may have caused fragments to release from the sheath.

The second observation that can be made is that the thickness of the ice accumulation does not need to be 1/4” for shedding to occur. In the January 2015 event, shedding occurred even though the ice accumulation was only 1/8” thick. The thickness did seem to have an effect on the way the ice layer shed from they stay sheath. With thick ice accumulation, shedding typically occurs in large sheets of ice and the result is shedding of an entire sheath in the matter of minutes. However, in this event the ice released from the stay sheath in small fragments leaving behind the majority of the ice on a stay sheath.
Chapter 4

Sensor Evaluation and Development

4.1 Introduction

As it was mentioned in the previous chapter, there is not a viable active or passive technology when it comes to icing on cable stay sheaths. In Chapter 1, it was mentioned that cable collars could potentially be used as active control during and after a wet snow storm. Unfortunately this technology cannot be used on bridges that are affected by icing due to the cable collars sliding over the ice rather than removing it. With this said, the most viable option to manage stay icing is an administrative strategy. In this case, administrative strategy would be to monitor the weather conditions throughout an entire event in order to make informed decisions on when to close travelling lanes and how many to close in a particular direction. The closing of traffic lanes during time of shedding reduces risk to the travelling public.

Several variables regarding the microclimate on the bridge as well as the stay sheath condition must be known in order to help operations personnel to make informed decisions. The majority of variables, such as ambient temperature, stay sheath temperature, wind speed, precipitation amount, solar radiation, etc., can be collected
through commercial sensors. However, there are still two crucial variables regarding the condition of the stay sheath itself that must be determined in order to allow the monitoring system to be accurate; ice and/or wet snow thickness as well as the presence and state of water. In addition to helping operations personnel make better decisions with administrative strategy, field visits could potentially be eliminated by obtaining this information reducing the risk imposed on them by the winter weather events. This chapter will discuss the evaluation of several thickness sensors, the development of the UT Presence and State Sensor, and the lab and field tests for both the UT Optical Thickness Sensor and UT Presence and State Sensor.

4.2 Snow and Ice Maker

As mentioned in Chapter 1, there are two types of winter weather events that can affect bridges with above deck structure, which are wet snow and icing events. The wet snow events that the Port Mann Bridge has experienced are unique considering most events that are known pertain to icing on cable-stayed and suspension bridges. Therefore, it was decided to perform experiments using both wet snow and ice in order to learn more about the harsh winter weather events that are occurring worldwide. A simple machine had to be designed and developed so that the research team could create wet snow to simulate such an event considering wet snow events in the Toledo, Ohio area are not frequent enough to produce the needed data. The way the snow machine was designed also allows for the research team to produce ice when needed.
4.2.1 The Science behind Snow Making

There are several major factors to consider when making snow, which include wet bulb temperatures, droplet size, and super cooling. Although ambient temperatures play a major role in making snow, the more important variable to consider is wet bulb temperature. This is because ambient temperatures do not include the air humidity’s cooling effect whereas wet bulb temperatures do. Humidity is a reference to the amount of moisture currently present in the air. When high humidity is present, a water droplet’s surface cannot evaporate a small portion of water to remove any of the additional heat that is keeping it as a liquid rather than an ice crystal (“Snowmaking Science”, 2015). Furthermore, the likelihood of creating snow from a warm water source such as city water significantly decreases as the humidity increases. Figure 4-1 illustrates the correlation of ambient air temperature and humidity to the quality of snow that can be made. The ambient air temperatures are the numbers on the left and the wet bulb temperature are the numbers that are located in the chart. The “Good Snow Quality” refers to powder snow. The “Poor Quality Snow” ranges from low water content snow to slushy ice.
The other two factors feed off of each other. Droplet size is a vital factor in making snow because the smaller the droplet size is, the more likely it will freeze. This is due to the droplets surface area to volume ratio being larger, which consequently exposes more of the surface of the droplet to the cold air allowing evaporative cooling effects to form ice crystals (“Snowmaking Science”, 2015). Snow machines utilize nozzles that allow them to spray out water droplets at sizes around 40-50 microns. Super cooling takes place when the water stream is infused with the compressed air. The compressed air rapidly expands cooling the air around the mist. This ultimately forms tiny ice crystals out of the droplets through expansive and convective cooling effects. They work together because the rapid expansion from the compressed air is utilized by the droplets surface area. If the droplet size is too big, the expansive cooling effect will not be sufficient enough to convert the water to ice crystals and, therefore, snow will not be produced.

Figure 4-1: Ambient Temperature and Humidity Correlation to Wet Bulb Temperatures (“Snowmaking Science”, 2015)
4.2.2 Externally Mixed Versus Internally Mixed Snow Machines

There are two main types of snow machines that are plausible for outdoor experiments. The two types include external and internal mixing machines. Both types of snow machines both mix compressed air and water in order to create snow and/or ice (Tetra Tech EM Inc., 2002; Energy & Resource Solutions, 2004; SnowStorm Snowmaking, 2015). The main differences are where the two snow making components are mixed and atomized. External mixing systems spray the two components out of separate nozzles. This allows the compressed air and water to mix outside of the system. Once outside the snow machine, the compressed air atomizes the water creating tiny water droplets. The tiny water droplets that are formed through this process have a much larger surface area to volume ratio, which ultimately allows the water droplets to nucleate through expansive and evaporative cooling effects (Tetra Tech EM Inc., 2002; Energy & Resource Solutions, 2004; “Snowmaking Science”, 2015). The newly formed nucleation sites then attract large unfrozen droplets and experience convective cooling, allowing for snow to be formed.

As with every system, external snow machines have their advantages and disadvantages. The biggest advantage of applying this particular system to outdoor experiments is that water will never back up into the air line. This is a significant advantage because there is absolutely no risk of harming an air compressor considering the air and water are kept separately within the system itself. This would reduce “baby sitting” the snow machine if it were to be used for long durations of time. The biggest disadvantage to this system is that there is less experimental control. This due to the two components of snowmaking being mixed outside of the system. Making the necessary
adjustments to compensate for wet bulb temperatures and wind are difficult because the two variables fluctuate over time. Otherwise, the conditions in which this machine could operate are reduced resulting in less experiments.

As for internal mixing systems, compressed air and water are mix internally within the chamber of the snow gun (Tetra Tech EM Inc., 2002; Energy & Resource Solutions, 2004; SnowStorm Snowmaking, 2015). As the two components of snow making are being thoroughly mixed, the compressed air atomizes the water stream. This allows the tiny water drops to nucleate through expansive and evaporative cooling effects as it is exiting the nozzles of the machine. These nucleation sites then act as facilitators and freeze the remaining water droplets (Tetra Tech EM Inc., 2002; Energy & Resource Solutions, 2004; SnowStorm Snowmaking, 2015).

There are several advantages and disadvantages to using an internal mixing snow machine. The main advantage of applying this system to outdoor experiments is that there is more experimental control. This is due to being able to adjust the levels of compressed air and water entering the system, which ultimately allows for different types/structures of snow. This advantage is a necessity because it allows for more experiments to be performed at the field station throughout any given winter. The volume of compressed air used with this system dictates the water content in the snow (Energy & Resource Solutions, 2004). Furthermore, this concept can be used to create snow at a larger range of temperatures, e.g. when the temperatures during an experiment are warmer more compressed air can be used to create smaller water droplets and vice versa. The major disadvantages of this type of system include potential freezing within the mixing chamber and water backing up into the air line of the compressor. These
particular disadvantages can be prevented by having a check valve on the air compressor (MakeSnow, 2015) and “baby sitting” the snow machine.

4.2.3 The University of Toledo Snow Machine Design

It was decided that an internal mixing snow machine should be built for the wet snow outdoor experiments. This type of snow machine was desired due to the amount of experimental control and a larger range of temperatures in which the snow machine could function. The aforementioned reasons ultimately allow the research team to perform more outdoor experiments throughout a given winter season, thus, resulting in more empirical data. Additionally, the experimental control allows for different wet snow structures, in terms of water content, to be studied. Different snow structures may play a major role in the adhesiveness of the wet snow, e.g. the snow will not stick to the surface of a sheath if it is too dry.

The internal mixing snow machine was built using both brass and stainless steel high pressured fittings with a pressure rating higher than 2000psi. The fittings that were used to build the snow machine gun seen in Figures 4-2 and 4-3 below include: one nucleation nozzle, one 1/4” T fittings, one1/4” street elbow, three 1/4 ” pipe nipples, one1/4” globe valve, one air pressure regulator, and one1/4” air quick connect. In addition to the aforementioned fittings, an air compressor was used in order to complete the design of the snow machine.
Figure 4-2: Snow Maker, Side View

Figure 4-3: Snow Maker, Top View
All fittings are rated at 2000 psi due to the initial design incorporating a pressure washer. The pressure washer was believed to allow more snow to be made faster due to the pressurized water volume being forced through the snow maker, however, the nozzle could not produce small enough droplets. Since the nozzle was not producing adequate size droplets, the droplets stayed in liquid form and snow could not be made. The globe valve and air pressure regulator was added to the snow maker in order to have control over the air to water ratio. This ultimately allowed for different snow structures to be made as well as for experiments to be performed in varying weather conditions. Figure 4-5 below illustrates how the snow maker produces wet snow accumulation.

Figure 4-4: Place Holder for Schematic
4.3 The University of Toledo Presence and State Sensor

4.3.1 Importance of the UT Presence and State Sensor

As previously mentioned, the presence and state of water on the stay sheath is a variable that is currently unknown during winter weather events. There are two commercial sensors that shed light on this issue, however, they do not make contact with the stay sheath, which can ultimately lead to ambiguous data. The accurate data pertaining to the presence and state of water on the stay sheath is considered to be invaluable. This is because water in the interstice between an ice layer and the sheath is a precursor to shedding. As mentioned in Chapters 2 and 3, shedding can occur even if the temperatures are below freezing. This is due to solar radiation penetrating the ice, warming the stay sheath, and creating a greenhouse effect between the ice layer and sheath. When this greenhouse effect occurs, water is present in the interstice due to the
heating of the stay sheath melting the ice layer through conduction and radiation heating effects. Furthermore, the presence of water in the interstice, whether present due to solar radiation heating the sheath or ambient air temperatures, can be utilized to predict a time window when shedding may occur. This would allow operations personnel to make informed decisions in an efficient manner when it comes to lane closures.

Two commercial sensors that can shed light on this information are the Goodrich Ice Detector and the Leaf Wetness Sensor (LWS). In the case of the VGCS, they have both been deployed onto the bridge. The Goodrich Ice Detector has the ability to detect ice presence on the bridge where it is located as well as determining ice thickness. However, the Goodrich Ice Detector includes a heater which removes the ice from the sensor upon reaching a prescribed threshold of thickness so as to avoid damaging the sensor; without proper bookkeeping of these heating events, the detector cannot monitor ice persistence. Ice persistence is typical during icing events and having this knowledge without having to send operations personnel on-site for stay evaluations multiple times a day reduces the risk of injury. Additionally, the ability to detect ice accumulation on the stay sheaths itself can be misleading. This is believed to be due to ice accumulating on a small sensing element rather than a large diameter cylindrical sheath. The accretion rates can differ due to the vastly different surface areas that the two objects have. However, accurate ice thickness may be possible to achieve through calibration. Figure 4-6 shows a schematic of the Goodrich Ice Detector.
The other sensor that was deployed in order to gain insight on the presence and state of water on the stay sheaths was the LWS seen in Figure 4-7 below. The LWS has the ability to determine the state of water on its surface by measuring the dielectric constant of what is on its surface. All mediums have different dielectric constants, e.g. water’s is 80, ice’s is 5, and air’s is 1. The sensor outputs a millivolt signal proportional to the material’s dielectric constant on the LWS’s surface (Decagon Devices, 2015). Therefore, the sensor potentially has the ability to determine the presence and persistence of ice on its surface. The LWS is an agricultural irrigation aid designed to mimic the water collecting behaviors of a leaf. It is made of coated fiberglass, which has different thermal properties than that of both HDPE and stainless steel stay sheaths. Hence, the information that is outputted from the sensor can be misleading in regards to the stay sheath condition. Thermal radiation from the sun is one of the triggers of ice shedding. The radiation can cause a material like stainless steel to heat 20-30°F higher than the
freezing point of water. Additionally, the LWS has been said to be minimally sensitive to ice and snow (“7-Day Surface Moisture, 2015), thus, data outputted by this sensor is ambiguous.

Figure 1-7: Leaf Wetness Sensor (Decagon Devices, 2014)

Taking all this into consideration, it was decided that a sensor needed to be designed and developed in order to adequately determine the presence and state of water on the surface of the cable-stay sheaths. The main goal was to develop a sensor that is aesthetically pleasing, adheres to the cylindrical shape of a stay sheath, can obtain accurate temperature at the point it is located, is flat and not bulky, and is able to produce the needed data regarding the presence and state of water on a stay sheath.

4.3.2 How the UT Presence and State Sensor Works

The University of Toledo Presence and State Sensor works by utilizing the electrical properties of air as well as the different states of water, specifically, the conductive properties. The different states of water that are of interest during an icing or wet snow weather event are water, water and ice mix, and ice. Air is also of interest considering if the sensor is reading air, then the stay sheaths are more than likely not
covered in ice or wet snow. Also, air would indicate that the ice or snow accumulation has either shed or sublimated. The order of the mediums from most conductive to least conductive are as follows: water, water and ice mix, ice, and then air.

By utilizing the conductive properties of water, water and ice mixture, ice, and air in a basic circuit, it is possible to differentiate which medium is present on a surface. To further explain how the conductivity plays a major role in the functionality of the sensor, a diagram was created. In Figure 4-8, it can be seen that there is an open circuit that includes a power source, wires, and a data acquisition system. An open circuit does not provide any information to the DAQ because the current supplied by the power source does not proceed past the gap. However, if the two ends of the wires were put into a medium such as water, it would close the circuit and allow the DAQ to read a voltage. Resistance is the inverse of conductivity (Resistance = 1/conductivity). When combining this relationship and basic electrical engineering principals, it is possible to design a sensor that determines the presence and state of water on a surface.

Figure 4-8: Basic Open Circuit Schematic
4.3.3 UT Presence and State Sensor Prototype Design

There are two pieces that had to be designed in order to create a sensor that can detect the presence and state of water on a surface. The first part was the circuit, which can be seen in Figure 4-9 below. The circuit has a power supply that provides an input voltage ($V_{in}$), a fixed resistor ($R_F$), a DAQ that reads the output voltage ($V_{out}$), and a place where the sensor is located. The sensor acts as a variable resistance ($R_V$) because the resistance present at the sensor is dependent on the medium (air, water, ice, etc.) that is used to close the circuit. The DAQ is used to read the voltage across the known resistance.

![Figure 4-9: Circuit for the UT Presence and State Sensor](image)

The output voltage is dependent on the medium that is closing the circuit. This is because Ohm’s Law comes into effect as seen in the following equations. In the first equation, the voltage is equal to the current times the total resistance of the circuit. The resistors are in a series, thus, they are added to one another. However, in the following equation there is only one resistor that needs to be considered due to how the DAQ system is tied into the circuit. When determining the current in the circuit, the resistance of the entire circuit needs to be considered because all current is being forced to travel...
over the fixed resistor (R_F) as well as the variable resistance (R_V). Since the DAQ is only reading over one resistance and the current cannot change, the voltage varies.

\[ V_{out} = I R_F \rightarrow I = \frac{V_{out}}{R_F} \]  \hspace{1cm} (1)

\[ V_{in} = I R_T \rightarrow I = \frac{V_{in}}{R_T} \]  \hspace{1cm} (2)

\[ R_T = R_F + R_V \]  \hspace{1cm} (3)

Using the above relationships, the output voltage can be calculated as follows:

\[ \frac{V_{out}}{R_F} = \frac{V_{in}}{R_T} \rightarrow V_{out} = \frac{V_{in} R_F}{R_T} \rightarrow V_{out} = \frac{V_{in} R_F}{R_F + R_V} \]  \hspace{1cm} (4)

The resistances, R_F and R_V, can be altered through design in order to clarify voltage output readings. Sometimes this is desired due to how close ice and air readings can be, which is caused by their conductivities being close to one another. To clarify the readings, a larger fixed resistor can be used.

The second piece that needed to be designed was the sensor, which can be seen in Figure 4-10 below. The sensor is made of a K-type thermocouple, several terminal strips, and wire. The thermocouple has an adhesive backing that allows it to stick and conform to all surfaces. The adhesive used on the thermocouple backing is very strong and is evident as several UT Presence and State Sensors have been used on VGCS sheath specimens at Scott Park for approximately two years before being removed. The thermocouple allows for the temperature at the location of the sensor to be determined, which is critical for two reasons. The first is because rising sheath surface temperatures create a presence of water in the interstice between the ice layer and sheath. This can be
indicative of imminent shedding. The second reason temperature is important is because it verifies the state of water. If the thermocouple is reading a temperature of approximately 28°F or below while an event is happening, then ice is present on the sensor where as if the thermocouple is reading a temperature of 36°F or higher when an event is occurring, then water is present on the sensor. Anything in between is considered slush/snow (water and ice mixture). The sensing terminal is considered the variable resistance ($R_V$) and allows for the presence of air or water/ice to be determined through its conductivity/resistance, while the temperature determines the state of the accumulation, as described above.

Figure 4-10: UT Presence and State Sensor, Prototype (Likitkumchorn, 2014)

4.3.4  UT Presence and State Sensor Prototype Ice Experiments

In order to determine if the sensor that was created was acceptable for bridge implementation, there were several ice accumulation and shedding experiments performed on the VGCS specimens at the field station. Specimen setup and experiment method can be found in Chapter 2, Sections 2.5.2 and 2.6.1. The specimen that was used during these particular experiments was instrumented with an UT Presence and State
Prototype Sensor array. The array allowed for four individual UT Presence and State Sensors to be used. As seen in Figure 4-11, the locations of the sensor around the diameter of the specimen were the top (12 o’clock), the east (3’clock), the bottom (6 o’clock), and the west (9 o’clock). This specific setup allows for solar radiation effects and water presence to be tracked around the diameter of the specimen.

**Figure 4-11: UT Presence and State Sensor Orientation on Field Specimens**

The DAQs that were used at Scott Park during the 2012-2013 winter when the icing experiments were performed were the MicroStrain V-Link and TC-Link. These particular DAQs were selected because they are wireless, which makes them easy to use during outdoor experiments. The UT Presence and State Prototype Sensor array was hooked up to the MicroStrain V-Link, which provides 7 mV to the sensors. This DAQ was set to read the output voltage so that the presence and more importantly state of water could easily be determined through there conductive properties. The MicroStrain TC-Link was used in order to capture the data from the K-type thermocouples. Due to the way the DAQ system was setup, the voltage was not recorded, but rather the raw
counts were logged. Therefore, this section will provide sensor output in raw counts, which has a linear relationship to output voltage.

4.3.4.1 Icing Experiment, February 16, 2013 – February 17, 2013

As mentioned in Chapter 2, a typical icing experiment typically lasts between 4-10 hours determining on the accumulation desired and the weather conditions throughout the icing experiment. For this experiment, a high ice accumulation was not necessary. This is because the main point of this particular test was to cycle the sensor and see its response. The total accumulation time was only about 2.5-3 hours. Through experimentation, it has been determined that a typical threshold for ice to shed is a 1/4 inch. For ice accumulation of a quarter inch to occur, water must be misted for approximately 4 hours and temperatures must be in the lower 20s degrees Fahrenheit. In this experiment between an 1/8 and a 1/4 inch of ice was accumulated.

Figure 4-12: Icing Experiment with UT Presence and State Sensor (Likitkumchorn, 2014)
Figure 4-13: UT Presence and State Prototype Sensor Data (Likitkumchorn, 2014)

Note: For Figure 4-13, UT Icing refers to UT Presence and State Sensor.

The output data from the UT Presence and State Prototype Sensor can be seen in Figure 4-13 above. There are four sections of the graph that represents an entire event. The first part, section A, is prior to the start of the experiment. Two observations can be made which are the specimen temperature was around 21°F and the raw counts were low. The specimen temperature is critical to monitor because the lower the temperature, the faster the accretion rate of ice is. Additionally, it can be seen that the thermocouple is around 7.5 raw counts. This is indicative of air.

The second part, section B, illustrates the part of the experiment where water was misted onto the specimen, which started around 4:45-5am. It can be seen that the specimen temperature rises approximately 11°F. This is typical when water is being misted onto the specimen because of the latent heat transfer from the warmer tap water to the cold specimen. The raw counts increase significantly to approximately 38-39, which
indicates the presence of water on the stay sheath. Both the temperature and the raw counts decrease as the experiment continues. This is because the state of water transitions from water to solid ice. When ice is present, the raw counts decrease because the conductivity is reduced and the temperature of the stay sheath decreases because the latent heat from the tap water is no longer making contact with the stay sheath.

The third part of Figure 4-13, section C, shows how the ice covered stay sheath reacts when the sun rises around 7:45am. The raw counts and temperature outputted from the UT Presence and State Sensor begin to increase again. This indicates that water is present under the ice layer. It was reported in Likitkumchorn (2014) that the ambient temperature was approximately 28°F throughout the day, thus, the water was caused by solar radiation. As previously mentioned, the ice was not accumulated to the thickness threshold for shedding to occur. This section of the graph shows that water was present, which is typically a good indicator of shedding, but because the ambient temperature was not above freezing and the ice layer was below the thickness threshold, shedding did not occur.

The final part of the graph, section D, is indicative of ice persistence. The ice never completely shed to expose it to the air or wind. Exposer of water to the wind or the air during the day time usually allows the specimen to dry off. In this case, the ice persisted and the water in the interstice refroze. This is indicated by the raw counts returning to 20-25 and the specimen temperature returning to approximately 16-20°F after the sun set.

In conclusion, the UT Presence and State Sensor was tested successfully. It was able to correctly determine when nothing or air was present, when water was present, and
when ice was present on the stay sheath. Additionally, it was able to show that the ice persisted on the stay sheath. Most importantly, it was able to show the moisture at the interstice change from water to ice and back again, through multiple cycles, all under an outer layer of ice. This is data that no commercial sensor is able to produce.

4.3.5 UT Presence and State Sensor Prototype Wet Snow Experiments

Experiments utilizing wet snow on a HDPE sheathing specimen were also performed at the outdoor field station. These particular experiments were performed in order to test the UT Presence and State Prototype Sensor with a medium that is more of a slush (ice and water mixture). The detection of such a medium would be useful for bridges that also experience wet snow and not just ice. The use of a HDPE specimen also allowed the research team to study the effect of solar radiation on a typical sheathing material used by bridges around the world.

The specimens utilized for this experiment were made from HDPE, had a diameter of approximately 8 inches (20 cm), and were 4 feet long. The specimen was supported and angled at 30° by using stacked cinder blocks. Unlike the VGCS sheathing specimens, the HDPE specimen is lightweight, thus, there was not a need to fill the blocks with reinforcement and concrete. The specimen was instrumented with a UT Presence and State Prototype Sensor array as seen in Figure 4-11 above, a solar radiation sensor array, and a LWS. The solar radiation sensor array was setup in the same orientation as the UT Presence and State Sensor (Figure 4-11). The solar radiation sensor outputs voltage depending on how much sunlight reaches it. These sensors were used to track the amount of light during the experiment. The LWS was attached to the 12 o’clock position at the top of the stay seen in Figure 4-14 below. It was used as a
reference as well as a comparison to the UT Presence and State Sensor. Additionally, there was a metal frame setup as seen in Figure 4-15. This frame was setup over the HDPE stay sheath in order to do thickness sensor evaluation. It housed the laser for the UT Optical Sensor as well as both ultrasonic sensors that were tested. The results of the thickness experiments are summarized in Sections 3.4 and 3.5 and a full detailed report can be found in Likitkumchorn (2014). Figure 4-14 shows the location of the LWS as well as how the UT Presence and State Sensor and Solar Radiation Sensor are located adjacent to each other. Figure 4-15 illustrates the frame’s position in accordance to the HDPE stay sheath.

Figure 4-14: HDPE Specimen Setup (Likitkumchorn, 2014)
There were several wet snow experiments that were performed during the 2013 – 2014 winter, however, only one is presented in this thesis in order to discuss the typical findings and fundamentals with the UT Presence and State Sensor and wet snow. For additional experiments and a full detailed report on wet snow experiments held at the Scott Park field experiment station please refer to Likitkumchorn (2014).

The experiments utilized the snow maker described in detail above. The snow maker was useful in terms of performing more experiments. This is due to its ability to adjust the amount of air and water used. Typical accumulation rates are 4 inches per hour using the snow maker, which is much faster than ice accumulation. Additionally, the same DAQ system that was used in the icing experiments in the previous section was utilized during the wet snow experiments. The LWS was also connected to the MicroStrain V-Link DAQ as it has a similar electrical circuit as the UT Presence and State Prototype Sensor. The data was recorded in raw counts.
Wet snow was accumulated during the night of March 13, 2014 and shedding took place the following morning. The goal of this particular experiment was to accumulate a large thickness on the top of the HDPE specimen. The experiment started at 9:36pm (21:36) and the snow maker was stopped just over two hours later at 11:45pm (23:45). During that two hours of accumulation, the wet snow reached a thickness of approximately 8 inches. In order to ensure that wet snow had indeed been generated, three containers with known volumes and mass were placed beneath the HDPE specimen. After the containers were completely filled with the snow that was generated by the snow maker, they were weighed. Since both the volume and mass of the snow were known, the average density was able to be determined. The average density of snow made in this experiment was 208.7 kg/m$^3$, which is considered wet snow since it was above the 100 kg/m$^3$ threshold. Figure 4-16 below shows the wet snow accumulation on the top of the HDPE stay sheath.

Figure 4-16: Wet Snow Accumulation on the Top of HDPE Sheath (Likitkumchorn, 2014)
Figure 4-17: Data Output from the LWS and the UT Presence and State Prototype Sensor (Likitkumchorn, 2014)

Note: For Figures 4-17 and 4-18, Icing Top refers to UT Presence and State Sensor located on the Top, Icing East refers to UT Presence and State Sensor located on the East, and so on. Additionally, in this experiment the resistor size for the circuits were decreased in size. This made the raw counts for air to be measured at 20.5 counts.

Figure 4-17 above, compares the data captured by both the UT Presence and State Sensor and the LWS. The UT Presence and State Sensor easily was able to determine both the presence and state of the wet snow throughout the entire experiment. The peak on the left for the UT Presence and State Sensor located on the top illustrates when the snow maker started to spray wet snow onto the specimen. The peak decreases as the experiment continues due to the initial snow layer freezing to more of an ice rather than a snow structure and the subsequent layers not making contact to the surface of the sensor. Once the snow maker is stopped, the entire accumulation is allowed to freeze without additional moisture being added from additional layers, hence, why the raw counts decrease and maintain to be logged as 20.75. Additionally, the other sensors consistently
read low raw counts that indicate air throughout the entire experiment. This is because only a very light dusting to no snow was covering the sensors. Finally, the large peak on the right is indicative of water presence under the snow layer at approximately 10:15 am. This is due to the increase in ambient air temperature and solar radiation. Shedding occurred shortly after at 11:35am, which is indicated by the small peak at the very right of the plot above. It should be noted, that the UT Presence and State Sensor had an output voltage or counts which corresponds to air prior to the shedding event. This shows that there was separation between the snow accumulation and sheath, thus, providing a window of warning for potential shedding.

The LWS gave similar output data as the UT Presence and State Sensor. However, the peak for when water was present occurred nearly an hour after the UT Presence and State Sensor indicated water was present. Additionally, the sensor does not provide an early warning to potential shedding. Both of these outcomes are because the LWS is not making direct contact to the stay sheath.
Figure 4-18: Data Output from the top UT Presence and State Prototype Sensor (Likitkumchorn, 2014)

Figure 4-18 above compares the data output from the thermocouple and the sensing terminal of the top UT Presence and State Sensor. Similar to the icing experiments, the temperature increased when the experiment began due to the latent heat from the wet snow produced by the snow maker. This temperature then decreased as the initial layer froze and continued to do so after the accumulation portion of the experiment was stopped. Once again this is because moisture is no longer being introduced into the accumulation. As the sun rises and solar radiation and ambient temperatures increase, the temperature of the sheath does as well. When the stay sheath temperature increases, water presence is indicated by the sensing terminals. After the wet snow accumulation sheds, the stay sheath temperature continues to increase and the sensing terminals give output raw counts indicating the presence of air.

One major observation can be made from this graph. The first is the presence of a “thermal lag,” which is when the temperature increases to 32°F while the presence of
water in the interstice between the layer of snow and sheath develops. This phenomenon occurs during phase changes as seen in the graph above (Koenig, G. G., and Ryerson, C. C., 2011; Ryerson, C.C., M. Wyderski, D. Tarazano, and J. Davila, 2003). The first appearance occurs during the phase change from wet snow to dry snow/ice and the second occurrence happens during the phase change from dry snow/ice to water. This “thermal lag” could potentially be used as an early warning for imminent shedding. Wet snow accumulations are much heavier than the ice accumulations seen on the VGCS. Furthermore, the likelihood of wet snow shedding once the presence of water occurs is higher than that of the same situation, but with ice. Further investigation would need to be done before declaring the “thermal lag” phenomena a sure bet for shedding.

The final observation that can be made for this experiment is the way the wet snow shed from the specimen. The bulk of the accumulation was directly centered on the top of the specimen, however, the shedding occurred on the west side as seen in Figure 4-19. This is a fairly typical shedding pattern, whether ice or wet snow, because the sun heats up the specimen and solar radiation begins to melt the accumulation on the east side. This shifts the center of gravity more towards the west of the specimen. The weight of the snow then forces it to shed.
4.3.6 UT Presence and State Sensor Revised Design

The UT Presence and State Sensor prototype was successfully tested in both the laboratory and the field. However, there were several issues that needed to be addressed before the sensor could be implemented onto the bridge. The issues included: local ice build-up, long term durability, aesthetics, and lack of interchangeability. As seen in Figure 4-10 above, the way the sensor was initially built using terminal strips allowed for local ice build-up at the sensing terminals. This is due to the solder creating raised bumps where the presence and state measurements were being taken. The raised bumps have the potential to trap water, thus, relaying misleading information during the initial
stages of an event. The second issue that needed to be dealt with was the corrosion that was occurring to the sensing terminal. This corrosion damages the sensor and jeopardizes its long term durability. Although several prototype sensors were left at the field station for two years and were still sticking to the VGCS stay sheath specimen, they were highly corroded. The final major issue that needed to be addressed is the interchangeability of the sensor. The prototype sensor, which consists of a circuit, thermocouple, sensing terminal, and wire, is created as one unit. Additionally, if the prototype would have been deployed on the bridge, more than likely an array of four sensors would have been made from an 8 wire cable in order to keep a clean look for aesthetic purposes. This setup would be detrimental if something were to go wrong with an individual sensor because an entire array would have to be removed. Therefore, the UT icing research team began the development of a new version of the UT Presence and State Sensor in order to present a reliable and deployable sensor.

To improve the sensor design, materials were investigated and purchased. The first major design decision was utilize adhesive tapes rather than common adhesive epoxies. This decision was made after seeing: 1.) The success of the thermocouple’s adhesive tape in the field and 2.) How easy it was to deploy the prototype sensor in the field because common epoxies were unnecessary. Taking this into consideration, an adhesive tape that would allow the sensor to be placed onto a stay sheath for a long duration of time was sought after. The research team eventually came upon an outdoor flashing tape that can be seen in Figure 4-20 below (white backed tape on left). This tape is extremely adhesive and weather resistant.
The second design decision was made to eliminate both the local ice build-up and corrosion problems by using a copper tape that had a 1/4 inch width, which can be seen in Figure 4-20 (middle tape). Copper tape is conductive, and therefore, can be used for the sensing terminals. In the revised design, the copper tape is 2.5 inches long, allowing for the wires to be soldered several inches away from the sensing terminals. This ultimately eliminates the local ice build-up at the sensing terminals, thus, providing more accurate data. For aesthetic purposes, a silver outdoor foil tape was purchased as seen in Figure 4-20 (tape on the right). This tape is placed on the top of the sensor so that the UT Presence and State Sensor can look aesthetically pleasing on the bridge. This particular tape can be interchanged depending on the stay sheath color.

![Image of tapes](image)

**Figure 4-20: Tapes used in the Revised Design of the UT Presence and State Sensor**

To address the issue of interchangeability, weather proof connections and a caulking was used for field experiments. The connection seen in Figure 4-21 allows two wires to be connected by placing each wire in one of the ends and then crimping them into position. A heat gun can then be used to heat shrink the ends closed to provide
weather protection to the wire connection. The caulking also seen in Figure 4-21 below was used to provide additional weather protection. For better interchangeability, a waterproof connection that screws shut and is not too bulky is being researched.

![Caulking and Connector](image)

**Figure 4-21: Wire Connections and Caulking for Revised Sensor Design**

There are four steps that need to be done in order to create the revised UT Presence and State Sensor. The first step is to cut two rectangles out of the outdoor flashing tape. The overall dimensions are 1”x2.5.” Additionally in this step, a square hole that is roughly 1/4”x1/4” needs to be cut out of one of the rectangles. The hole that is created is for the thermocouple’s cold junction and it will allow the thermocouple to read the surface temperature on the stay sheath where the UT Presence and State Sensor is located. The second step is to place the thermocouple onto the outdoor flashing tape with the hole. In this step the cold junction needs to be placed where the hole is in order for the thermocouple to work properly. The third step is to place two copper strips that are 1/4”x2.5” and solder the wire to them. Theses copper strips are placed roughly 3/8” apart center to center. The final step is to waterproof the copper strips and solder joints.
This is done using two methods. A water proof coating is applied on the 3/4 of the copper strips starting from the bottom. Then the second 1”x2.5” rectangle from step one is applied over roughly 95% of the copper strips as seen in Figure 4-22 (D) below. Note, the copper in Figure 4-22 (D) has to remain exposed in order to be able to read the presence and state of water, thus, it is not weather proofed with the coating or the flashing tape. Figure 4-22 illustrates the steps mentioned above and Figure 4-23 shows the dimensions used for the revised design of the UT Presence and State Sensor. For Figure 4-23, (A) illustrates the sensor without a top covering, which shows the spacing of the copper tape strips and the placement of the thermocouple; (B) shows the revised design of the sensor from above with the top covering; (C) shows the dimensions of the hole cut out of the bottom layer of the tape in order to allow the thermocouple to take readings of the sheaths surface temperatures.

![Figure 4-22](image)

**Figure 4-22: The Creation Stages of the UT Presence and State Sensor**
4.3.7 UT Presence and State Sensor Revised Design Lab Results

The revised design of the UT Presence and State Sensor was tested in the laboratory to ensure that it was working properly before being used in outdoor experiments. The DAQ used for this experiment was the Campbell Scientific CR10X. This DAQ is different than what was used for the outdoor experiments, however, the sensor’s functionality can still be verified by using it. The reason for this is because the correlation of the voltage output for each medium tested (air, water, and ice) should be the same as any other DAQ used. The only difference is the amount of power supplied, which scales the output voltage. For example, the National Instruments DAQ used in the field experiments provides 5 Volts to the sensors, thus, the following could be expected: air = 0 Volts, ice = 0.2-0.8 Volts, and water = 4-5 Volts. Whereas the Campbell Scientific CR10X provides 2.5 Volts to the sensors, therefore, the following would be expected: air = 0 Volts, ice = 0.1-0.4 Volts, and water = 2.0-2.5 Volts.

The way this experiment was performed was by sticking the UT Presence and State Sensor into a rectangular container as shown in Figure 4-24 (A). It was fixed to the bottom of the container using the adhesive backing of the outdoor weather resistant tape.
The container was then filled with water approximately 1/4” deep as seen in Figure 4-24 (B). The container was then placed in the icing tunnel’s cold room and allowed to freeze for over 24 hours. After the freezing period, the container was taken out of the icing tunnel’s cold room and thawed back to water at room temperature. Figure 4-24 (C) is a photograph that was taken directly after removing the container from the icing tunnel’s cold room. A 1/4” of ice is completely covering the sensor.

![Photographs from Laboratory Experiment](image)

**Figure 4-24: Photographs from Laboratory Experiment.** (A) shows container empty so that the voltage output for air could be verified. (B) illustrates container with water so the voltage output for water could be verified. (C) shows the water turned to ice so that the voltage output for ice could be verified.

The results from the laboratory testing of the UT Presence and State Sensor can be seen in Figure 4-25 below. The peak and plateau of approximately 1.6 Volts at the left indicates the presence of water on the surface of the sensor. Theoretically, this voltage should read 2.0 Volts or higher, however, purified bottled water was used in this experiment. The impurities of purified bottle water are different than that of standard tap water thus, creating a difference in output voltage. This is when the room temperature water was poured into the container. The peak then decreases to a low voltage (0.1),
which is showing that ice is covering the surface of the sensor. This occurred after several hours in the icing tunnel’s cold room. The sensor’s output voltage then peaks again reading as high as 2.1 Volts, indicating the presence of water again. The voltage is higher than the initial 1.6 Volts due to dirt from the container getting into the water. Once again this would slightly change the impurities of the water being used, therefore, changing the output voltage. This was after about 45 minutes of thawing at room temperature. The sensor was adequately able to determine the presence and states of water in the laboratory, thus, it was implemented at the field experiment station for field testing.

![UT Presence and State Sensor, Laboratory Results](image)

**Figure 4-25:** Results from the UT Presence and State Sensor Laboratory Experiment
4.3.8 UT Presence and State Sensor Revised Design Ice Experiments

After the newly designed UT Presence and State Sensor was tested successfully in the laboratory, an array of them were implemented onto a VGCS sheath specimen at the outdoor testing station so that full scale icing experiments could be performed. The icing experiments were conducted in the same manner as described in Chapter 2. The VGCS specimen was instrumented with an array of four of the revised design UT Presence and State Sensors as well as an array of eight photosensors. The array of UT Presence and State Sensors was oriented with one at 12 o’clock, 3 o’clock, 6 o’clock, and 9 o’clock as seen in Figure 4-11 above. The photosensor array was oriented with one at every 45° starting at 12 o’clock seen in Figure 4-26 below. Additionally, a frame was built and placed above the VGCS specimen. This frame’s main purpose was to house the laser for the UT Optical Sensor. Figure 4-27 below shows the experimental setup.

Figure 4-26: Photosensor Orientation on Field Specimens
4.3.8.1 Icing Experiment, March 6, 2015 – March 7, 2015

The first outdoor experiment utilizing the revised design of the UT Presence and State Sensor occurred from March 6, 2015 – March 7, 2015. Ice accumulation started at 11:30pm on March 6 and the misting of water onto the specimen was stopped at 4:00am on March 7. During this time, approximately a thickness of 1/4” of ice was achieved. Due to rising ambient air temperatures and solar radiation, the ice accumulation shed on March 7 at 12:40pm. There were two objectives during this experiment, the first was to cycle the newly design UT Presence and State Sensor through an icing experiment to validate that it was working properly and the second was to study the thermal effect of solar radiation on the sheath and how it corresponds to ice shedding.
Figure 4-28: Data Output for the Top UT Ice Presence and State Sensor vs. Ambient Air Temperature

Figure 4-29: Data Output for the East UT Ice Presence and State Sensor vs. Ambient Air Temperature
Figure 4-30: Data Output for the West UT Ice Presence and State Sensor vs. Ambient Air Temperature

There are three main sections that need to be discussed in the Figures 4-28 – 4-31 above. The first section, labeled A, indicate the period where ice accumulation was started. The top, east and west sensors are all initially reading 0 Volts, which is indicative of the presence of air. They then rise to peaks that measure between 4 and 4.2 Volts; indicating the presence of water on the surface of the sensors. It can also be noticed that the peaks gradually decrease over time. This decrease in voltages is caused
by the freezing of the initial layers of ice, however, the sensors continue to output a high voltage in the range of 3-4 Volts because water is still being applied to them in order to accumulate a significant thickness of ice. The latent heat from the mist slightly melts the ice layers it makes contact with, which creates the presence of a water and ice mixture on the sensors rather than ice. As the accumulation grows, the bottom layers of the mixture continue to transition to ice due to stay sheath and ambient air temperatures. This is evident when looking at the thermocouple behavior during the accumulation stage of the experiment. The latent heat from the water mist warmed the specimen up to 32°F during ice accumulation. As the water transitioned to ice, the stay sheath temperature decreased.

Another observation that can be seen in the top, east, and west plots during this stage is that the sensors begin to completely read air (0 Volts), which is indicated in the plots with the symbol (1). This is believed to have occurred due to the electrical problem at Scott Park. The outside circuit of the experiment station would at times be overloaded due to a separate project. This would cause loss of power to the DAQ, therefore, causing data to be corrupted. The dashed red lines seen in section A of Figures 4-28 – 4-31 illustrate the probable path for the actual voltage output during this stage of the experiment. These paths are estimated based on past behavior observed in experiments utilizing the UT Presence and State Sensor. Figure 4-32 shows the ice accumulation over the entire specimen; the thickness was a 1/4".
The second section, labeled B, is the period of the experiment where ice accumulation had been stopped and the sun had not risen for the following day. During this time, the water and ice mixture is allowed to fully transition to ice. The output from the sensors decrease to the range of 0.4-0.8 Volts, which is indicative of ice. Throughout the night, the output from the sensors slightly decrease to 0.2-0.3 Volts; still showing that ice is present on the sheath.

The third section, labeled C, is the period where shedding occurred. March 7 was a cold day with clear skies. The ambient air temperature that was recorded from the Weather Underground station located at Reynolds Corners Toledo, Ohio shows that it was below freezing when shedding occurred, and therefore, shedding occurred due to solar radiation. The data shown in the graphs above indicate that solar radiation increased the stay sheath temperature to above the freezing point of water. The combination of heat conduction from the stay sheath and heat radiation from the sun melted the ice layer on the east and top of the specimen as seen in Figure 4-33 (A) and (B) below. By comparing the output data of the east, top, and west UT Presence and
State Sensor plots, it is possible to track the water presence on the stay sheath. The presence of water can be first observed on the east side of the specimen, then the top, and finally, the west. This is due to the sun’s location over time. The last observation to be made from the output data comes from the west UT Presence and State Sensor plot. The sensor’s voltage output first peaks at 4.2 Volts indicating the presence of water, then begins to read air (seen at point (2) in the plot above), and finally peaks at 3.5 Volts indicating the presence of water prior to shedding. The air reading is caused by the separation of ice from the sheath and the interstice drying out at that particular location as seen in Figure 4-34 (C) below. Shedding occurred at approximately 12:40pm March 7.

![Figure 4-33: Solar Radiation Causing Ice to Sublimate on East and Top of Stay Sheath](image)

There are several observations pertaining to shedding in this experiment that can be made. The first observation is the presence of water underneath the ice layer. Although the ambient air temperature was below freezing, the solar radiation warmed the surface of the ice to cause sublimation. Additionally, the solar radiation warmed the stay sheath to the point where heat conduction from the sheath to the ice layer was present.
causing the ice to melt. The ice melting through conduction created the presence of water under the ice layer. The second observation that can be made is the separation and rotation of the ice layer due to gravity. As the ice melts on the east and top of the stay, the center of gravity continuously shifts causing the ice layer to slightly rotate counter clockwise around the sheath’s surface. The weight of the ice is greater than the adhesion strength, therefore, separation begins to occur when the ice is rotating as seen in Figure 4-34 (C). The rotation and separation effect continues until the weight of the separated ice causes shedding.

![Figure 4-34: Photographs from March 7 Shedding Event.](image)

(A) shows both the presence of water and the line of separation caused by the rotation of the ice layer. (B) illustrates the presence of water under the ice layer. (C) portrays the separation and rotation of ice due to gravity. (D), (E) and (F) shows the shedding of the ice layer.
4.3.8.2 Icing Experiment, March 22, 2015 – March 24, 2015

The second outdoor experiment using the new design of the UT Presence and State sensor occurred from March 22, 2015 – March 24, 2015. Ice accumulation started at 10:50pm on March 22 and the misting of water onto the specimen was stopped at approximately 2:40am. During this time, an ice thickness a 1/4” was achieved at the locations of the UT Presence and State Sensors. The rest of the specimen was left untouched. The ice then persisted the following day, March 23, because the ambient air temperature did not rise above the freezing point of water and there were cloudy skies (lack of intense solar radiation). The night of March 23, the research team returned to the outdoor field station to increase the ice thickness on the specimen. Ice accumulation began at 9:00pm and the misting of water onto the specimen was stopped at 11:30pm. An ice thickness of 3/8” to 1/2” in the region of the sensors was achieved during this period of time. The rest of the specimen was misted until an ice thickness of 1/4” was reached. On March 24, the ice shed from the stay sheaths due to the combination of rising ambient air temperatures and clear skies (intense solar radiation). The goals of this experiment remain as before, which were to cycle the UT Presence and State Sensor to validate that it was functioning properly and to study the thermal effect of solar radiation on the sheath and its correspondence to shedding.
Figure 4-35: Data Output for the Top UT Ice Presence and State Sensor vs. Ambient Air Temperature

Figure 4-36: Data Output for the East UT Ice Presence and State Sensor vs. Ambient Air Temperature
There are four sections to be discussed pertaining to this experiment. The four sections are broken up and labeled in Figures 4-35 – 4-38 above. The first section, labeled A, is the period where ice accumulation was started. The top, east, and west UT Presence and State Sensors are initially reading 0 Volts, which indicates of the presence of air. The sensors then begin to read voltages in the range of 3-4 Volts, indicating the
presence of water. The top and the west sensors plateau at 4 volts and 3.5 Volts, respectively. Although they plateau and the output voltage indicates the presence of water on the stay sheath rather than ice, the accretion of ice is occurring. As described in the previous section, the latent heat of the misted water that is still being applied to the specimen during the accumulation stage of the experiment is slightly melting the ice layers below creating a presence of water in the interstice between the sheath and accumulated ice. The east and bottom sensors still indicate a presence of water, however, the water is not being directly sprayed onto them so the voltage output peaks at approximately 3 Volts and then significantly decreases. The substantial decrease is because the latent heat from the mist does not affect these particular locations, therefore, the water is allowed to freeze. The thermocouple output data also is consistent with the UT Presence and State Sensor as they read approximately 32°F when there is a presence of water on the sensors throughout the ice accumulation process.

The second section, labeled B, is the period of the experiment where the ice accumulation was allowed to freeze throughout the night, persist throughout the following day, and refreeze during the subsequent night. The UT Presence and State Sensors output initially decreases to approximately 0.1-0.3 Volts before the sun rises on March 23. This low voltage indicates the presence of ice on the sensors. Once the sun rises, all UT Presence and State Sensors output increases significantly, specifying that there is a presence of water on the surface of the sensors. However, ice persisted throughout the day due to ambient air temperatures below 32°F and the lack of intense solar radiation. It should be noted that the low amount of solar radiation did warm the stay sheath to 32°F. This caused the ice to melt through heat conduction from the sheath
and to sublimate due to heat radiation from the sun. However, ice shedding did not occur, hence, sublimation can be detected, but does not necessarily lead to imminent shedding.

The third section, labeled C, is the period where the research team returned to the field experiment station to increase the thickness of the ice on the specimen, therefore, leading to the spikes in voltage output for the UT Presence and State Sensors during the night of March 23. Ice was accumulated on the specimen until a thickness of 3/8” to 1/2” was achieved in the region of the UT Presence and State Sensors and 1/4” over the remaining surface area of the stay sheath. The accumulation was then allowed to completely freeze to the point where no water was present. The UT Presence and State Sensors voltage output was similar to section A of Figures 4-35 – 4-38, which shows that the sensor is consistently identifying the presence of water during ice accumulation. Figure 4-39 below shows an ice accumulation between 3/8” to 1/2” on the VGCS specimen.

![VGCS Specimen with Ice Accumulation between 3/8” and 1/2”](image)

**Figure 4-39: VGCS Specimen with Ice Accumulation between 3/8” and 1/2”**
The final section, labeled D, is the period where shedding occurred. March 24 was another cold day with clear skies. The ambient air temperature barely reached above freezing during the time ice shedding occurred. Although ambient air temperature was slightly above freezing, the primary reason for ice shedding is believed to be due to solar radiation. This is due to the way the ice shed from the specimen. The shedding pattern was nearly the same as the March 6 – March 7 experiment. The only difference is that the ice persisted for longer and the solar radiation had a more severe effect on the ice layer.

A new observation can be made from both the output from the top UT Presence and State Sensor and Figure 4-40 (B) and (C). As seen in Figure 4-35, the voltage output peaks at approximately 4.8 Volts indicating the presence of water, significantly decreases to about 0 Volts suggesting only air is present, peaks at 2.3 Volts specifying a wet ice (water ice mixture), and finally decreases back to 0 Volts indicating air is present again. This reason for this is shown in Figure 4-40 (B) and (C) where it can be seen that there is an ice layer that is present above the UT Presence and State Sensor, but the interstice is completely dry. This is also indicated by the thermocouple output considering the sheath temperature reaches 70°F when the UT Presence and State Sensor is reading air for the first time since before ice accumulation on March 22. This is caused by solar radiation creating a “greenhouse effect” within the interstice. Additionally, it was observed that the water that was melting from the ice layer travelled along the ice on the inside of the interstice, rather than dripping onto the stay and rolling off the side. Figure 4-40 (D), (E), and (F) illustrate the ice shedding from the west side of the stay sheath.
Figure 4-40: Photographs from March 24 Shedding Event. (A) shows the distribution of ice. (B) and (C) illustrate the interstice prior to shedding. (D), (E) and (F) shows the shedding of the ice layer

4.3.9 Corrosion Solution

The new UT Presence and State Sensor design eliminates local ice build-up, is aesthetically pleasing in the sense that it can blend in to whatever surface that it is on, and the sensors and/or circuits can be easily replaced due to the use of connections. However, corrosion of the sensor is still a problem. The corrosion occurs on the copper tape as seen in Figure 4-41 below. There is a simple solution that can be implemented immediately. The solution is to use the foil tape used for aesthetic purposes rather than the copper tape. The foil tape would work in the same manner as the copper tape because it is conductive. Additionally, it has been field tested to verify that it does not corrode. To implement this
solution, there would need to be minor laboratory testing in order to determine whether the voltage thresholds of air, water, water and ice mixture, and ice are the same as the copper tape. If they are different, then the fixed resistor would need to be either reduced or increased in size to compensate for the difference in voltage readings so that a clear output voltage value for each medium could still be produced.

![Corrosion on the Copper Tape](image)

**Figure 4-41: Corrosion Effects on the Copper Strips**

4.4 Determining Ice and Wet Snow Thickness

4.4.1 Importance of Ice and Wet Snow Thickness

The thickness of ice accumulation on a stay sheath is important when it comes to shedding events. In the past, ice accumulations greater than 1/4" caused sheets of ice large enough to impose significant damage to vehicles travelling the VGCS and accumulations less than 1/4" either melted in place or released in small fragments. Therefore, knowing the thickness of ice accumulations in combination with data pertaining to the microclimate of the bridge and presence of water on the sheaths allow
for efficient and effective administrative decisions to be made. Additionally, knowing the thickness of wet snow or ice accumulation on the stays of a bridge would allow for the elimination of on-site visits by operations personnel, which ultimately keeps them out of harm’s way during the harsh winter weather. Taking all of this into consideration, the icing research team evaluated two available commercial available sensors as well as designed and developed an optical thickness sensor.

4.4.2 Commercial Thickness Sensor Evaluation

There were two commercial sensors investigated that would allow for wet snow or ice accumulation on a stay sheath to be determined throughout a winter weather event. The sensors that were investigated were both ultrasonic thickness sensors. Ultrasonic sensors utilize the principal of echolocation in order to determine the distance between the sensor and an object. This principal can then be used to measure the change of distance over time, thus, allowing the thickness build-up of wet snow between the sensor and the stay sheath to be determined.

The first sensor that was investigated was the AGKU 1500 GI Ultrasonic Sensor illustrated in Figure 4-42 below. This sensor was lab and field tested in order to ensure the data output was accurate and reliable. There were three lab tests that were performed, which included current output, detection range and temperature compensation. The current output test revealed that the manufacturer’s specifications on both range and current output were inaccurate. The detection range experiment showed that the off-center range was broader than the manufacturer’s specifications as well as once again showing that the overall detection range was further than suggested. As for the temperature compensation test, as the temperature fluctuated over time the sensor began...
to read values fluctuating between ±5mm. This is not possible considering the test was performed during a period of time with zero precipitation. In addition to the lab tests, the field experiments proved that the AGKU 1500 GI was inaccurate in determining the thickness of wet snow on a test specimen. There was more than a 15% error, which is believed to be due to the lack of temperature compensation (Likitkumchorn, 2014).

Figure 4-42: AGKU 1500 GI Ultrasonic Sensor (Likitkumchorn, 2014)

The second sensor that was evaluated was the SR50AT Sonic Ranging Sensor seen in Figure 4-43 below. The SR50AT is also an ultrasonic sensor that was subjected to lab and field testing. There were two lab tests performed on this particular sensor, which included known thickness detection and temperature compensation. The sensor performed successfully in both tests. In addition to the lab tests performed, field experiments were carried out. In the field experiment, the sensor was able to accurately determine the thickness of wet snow on the test specimen (Likitkumchorn, 2014).
In conclusion, the SR50AT Sonic Ranging Sensor was tested successfully in both a lab and field setting. It was able to accurately determine thicknesses regardless of the harsh winter environment, therefore, they are judged to be field ready and deployable. It should be noted that the SR50AT has a significant downfall, which is that it requires a fixture that attaches to the stay sheaths. The sensor must be fixed roughly one meter away from the stay sheath surface, therefore, an adequate fixture that could withstand strong winds would need to be designed as well. However, the AGKU 1500 GI Ultrasonic Sensor wasn’t able to determine the thickness of wet snow on outdoor specimens accurately. This is due to the lack of temperature compensation. Therefore, the AGKU 1500 GI Ultrasonic Sensor has been ruled out and should not be used in the future without temperature compensation. Additional details regarding the testing and evaluation can be found in Likitkumchorn (2014).

### 4.4.3 UT Optical Thickness Sensor

The UT Optical Thickness Sensor was designed and developed by the University of Toledo icing research team. It utilizes a laser, a camera, and computer coding in order
to determine a thickness on any surface. The laser uses a lens to generate an expanded laser beam to map a surface profile. The camera then takes photographs throughout an event. Finally, the photographs undergo image processing in Matlab. The final result is an accurate thickness measurement.

For this process to work, two calibration photos need to be taken. The first is referred to as the “base photo,” which is where the laser is being projected onto the sheath surface without any accumulation (Figure 4-44 (A)). The second is referred to as a “known thickness photo,” which is a photo of the mapped laser line onto an object with a known thickness that is covering the sheath surface (Figure 4-44 (B)). After the calibration is completed, the camera can take pictures, which are referred to as “unknown thickness photos,” throughout an entire event. Furthermore, the “unknown thickness photos” undergo image processing so that the thickness can be determined at any point during a wet snow or icing event.

Figure 4-44: Photographs from March 6, 2015 – March 7, 2015 Icing Experiment. (A) shows the “Base Photo” for the UT Optical Sensor. (B) illustrates the “Known Thickness Photo” for the UT Optical Sensor (C) shows a typical “Unknown Thickness Photo” utilized by the UT Optical Sensor.

Figure 4-45 below is the calibration page of the graphical user interface (GUI) for the UT Optical Sensor. On this page a “Base Photo” and a “Known Thickness Photo” are selected for the calibration process. Once both pictures are selected, “Begin Calibration”
is clicked. The calibration works by determining the number of pixels between the laser line mapped in the “Base Photo” and the laser line mapped in the “Known Thickness Photo.” Since the thickness is known, the number of pixels per unit length can be determined. Figure 4-46 illustrates the calculation page of the GUI. On this page an “Unknown Thickness Photo” captured by the UT Optical Sensor camera is selected. The scale from the previous GUI page is then utilized to determine the thickness of accumulation at any point during a winter weather event.

Figure 4-45: UT Optical Sensor Calibration Process (Likitkumchorn, 2014)

Figure 4-46: UT Optical Sensor Calculation Process (Likitkumchorn, 2014)
The UT Optical Sensor was tested in both the laboratory and at the field experimentation station. In the lab setting, known thickness tests were performed on HDPE specimens. The UT Optical Sensor was able to accurately determine the thickness of several objects applied to the specimen. Additionally, the sensor was field tested with both wet snow and ice accumulations. In the wet snow experiments, the thickness sensor was well within a 5% error on all measurements, which is acceptable. In the icing experiments, the UT Optical Sensor was within 10% error on all measurements, which is also acceptable. The reason the UT Optical Sensor has a higher percent error during icing experiments is because the thickness of ice is significantly less than the thickness of wet snow accumulations. Furthermore, typical icing accumulations at the field experiment station are between 1/4” and 1/2” whereas the typical wet snow experiments are between 4” and 8.” Further details regarding the computer code as well as laboratory and field experiments utilizing the UT Optical Sensor can be found in Abdelaal (to be published).

4.5 Conclusion

There is data pertaining to a bridge’s stay sheaths that need to be collected in order to assist operations personnel make informed decisions when it comes to administrative strategy. Currently, the only way to check whether ice or wet snow accumulations are occurring on a bridge’s stays is manually considering the commercial sensors deployed on the bridge give ambiguous data pertaining to stay sheath condition. On-site verification places operations personnel in harm’s way during harsh winter conditions. By obtaining data regarding the presence and state of water as well as the
thickness of accumulations through sensors, on-site verification can be eliminated. Additionally, both the presence and state of water on the stay sheaths as well as the thickness of the accumulation play a major role in shedding. Obtaining this information may allow for a more efficient administrative strategy to be put in place. Taking this into consideration, the icing research team has evaluated potential commercial sensors. In addition to evaluating commercial sensors, two sensors were design and developed; one that determines the presence and state of water on a stay sheath and one that determines the thickness of either wet snow or ice on stay sheath.

The UT Presence and State Sensor has been designed, developed, and is ready for deployment. The sensor has been able to determine the presence and state of water in both laboratory and field experiments. In the laboratory, the state sensor responded well to a freeze thaw cycle as described in Section 4.3.7. In the field experiments, the sensor was able to detect ice and wet snow accumulation and water presence in the interstice prior to potential shedding. The sensor can potentially be utilized for early warnings to shedding. The revised design needs minor tweaking by replacing the copper tape strips with the foils tape strips. This would eliminate the potential of corrosion. In its current shape, it can last at least one winter season while collecting accurate data. Additionally, it should be noted that the cost of making the UT Presence and State Sensor is significantly less than the costs of sensors that provide similar data pertaining to the microclimate of the bridge.

Two available commercial ultrasonic thickness sensors were evaluated. The first sensor was the AGKU 1500 GI Ultrasonic Sensor. This sensor did not perform well in the outdoor experiments as it was unable to accurately determine the thickness of wet
snow. This is believed to be due to the lack of temperature compensation. Therefore it was ruled out and should not be used in the future without temperature compensation.

The second sensor evaluated was the SR50AT Sonic Ranging Sensor. This sensor tested successfully in both the lab and field experiments. It was able to accurately determine the thickness of wet snow regardless of the cold temperatures. However, this sensor must be fixed roughly one meter away from the stay sheath in order to work. This would require a fixture that could withstand the strong winds that are typical to bridge environments.

A thickness sensor was designed and developed by the icing research team. This sensor utilizes a laser, camera, and computer image processing in order to determine the thickness of ice or wet snow accumulations accurately. The sensor was tested successfully in both the lab and field setting. In the laboratory setting, the sensor accurately determined the thickness of foam samples with a known thickness stuck onto the surface of HDPE sheaths. In the field experiments, the sensor was within a 5% error when measuring the thickness of wet snow accumulations and a 10% error when measuring the thickness of ice accumulations, both of which are within a reasonable range.
Chapter 5

Conclusion and Future Work

5.1 Conclusion

In conclusion, three objectives were achieved in this thesis, which include: 1.) updating the VGCS case study with the most recent icing event that occurred in January 2015, 2.) documenting the evaluation and sensor development performed by the UT icing research team, and 3.) discussing the field experiments performed at the field station in the winter of 2014-2015. The January 2015 event was a major icing event that required all northbound lanes to be closed for a period of 8 hours due to ice shedding from the stay sheaths. Two observation can be made from this event. The first is shedding can occur when ambient air temperatures are below freezing and the skies are overcast. Unlike the five major events before it, the shedding event that took place in January 2015 happened with ambient air temperatures below freezing and overcast skies. It is believed that solar radiation caused the ice on the top of the stay sheath to melt shifting the center of gravity towards the east side of the stay during ice persistence. This shift of gravity allowed the ice layer to slightly rotate and separate from the stay sheath due to the gravitation force.
imposed by its own weight. The releasing of small fragments may have been caused by the wind catching the separated ice layer.

The second observation that can be made from this event is shedding can occur with ice accumulations under 1/4” thick. In the January 2015 event, an ice accumulation of 1/8” thickness caused ice shedding to occur. The thickness did have an effect on the way the ice layer shed from the sheaths. In past events, thick ice accumulations resulted in shedding of large ice sheets, which resulted in the shedding of an entire stay sheath in the matter of minutes. In this event, the thin layer of ice released in small fragments leaving behind the vast majority of the ice layer on the sheath.

The VGCS has been instrumented to where the microclimate is known, however, several variables relating to the condition of the stay sheaths need to be captured. The presence and state of water as well as the thickness of ice accumulation is still currently being checked manually. Although there are sensors, such as the LWS and Goodrich Ice Detector, that shed light on these unknown variables located on the bridge, they do not make contact to the stay sheath and can provide misleading information due to their shape and material makeup. The presence and state of water is considered to be invaluable when accurate because water in the interstice between the ice build-up and sheath is a precursor to shedding. Additionally, the thickness of the ice accumulation can determine the probability of ice shedding. Knowing the thickness of the ice accumulation on the bridge in combination to other weather data provided by other sensors implemented on the bridge can ultimately allow for bridge owners and operators to use administrative strategy efficiently. To obtain the needed information, the icing research team has designed and developed two sensors; one that has the capability of determining
the presence and state of water, and one that has the ability to determine the thickness of
the accumulation. In addition to the sensors that were designed and developed, the
research team evaluated two commercial sensors that can determine the thickness of ice
on a stay sheath via echolocation.

The first sensor that was designed was the University of Toledo Presence and
State Sensor. This sensor is a flat contact sensor that can be easily applied to the surface
of the stay sheath. It determines the presence and state of water through the electrical
properties of the different states (water, water and ice mixture, and ice). In addition to
being able to determine the presence and state of water, it consists of a thermocouple that
can read the surface temperature of the stay sheath at the sensors location. This sensor
has been tested in both the laboratory and field setting. The sensor has determined the
presence and state of water during numerous experiments. The UT Presence and State
Sensor has been developed in order to become more durable, aesthetically pleasing, and
to reduce ambiguous data output. Additionally, the cost of this sensor is significantly less
than that of a commercial sensor that can provide similar data pertaining to the
microclimate on the bridge. The UT Presence and State Sensor also provides data
pertaining to the stay sheath that no commercial sensor can capture.

The icing research teams also evaluated two commercially available thickness
sensors in the laboratory and field settings. Both of the commercial thickness sensors
were ultrasonic sensors. Ultrasonic sensors utilize the principal of echolocation to
determine the distance between the sensor and the questioned object. Echolocation can
be used to measure the change of distance over time, therefore, allowing the thickness of
ice or wet snow accumulations to be tracked. The first sensor evaluated was the AGKU
1500 GI Ultrasonic Sensor. Although this sensor showed promise in the laboratory setting, it was unable to accurately determine the thickness of wet snow accumulations during the field experiments, which is believed to have occurred due to the lack of temperature compensation. Thus, it was ruled out as a potential technology that could be implemented on the bridge and should not be used in the future without temperature compensation. The second sensor that was investigated was the SR50AT Sonic Ranging Sensor. This sensor was tested successfully in both the lab and the field settings. During the wet snow experiments, it was able to accurately determine the thickness of snow even at below freezing temperatures. However, it should be noted that this sensor needs to be fixed perpendicular to the stay sheath at more than three feet to work properly. This would ultimately require a fixture that can withstand strong winds that the bridge environment typically have.

The second sensor designed and developed by the icing research team was an optical thickness sensor. This sensor consists of a laser, camera, and computer coding that performs image processing on pictures taken by the camera in order to determine the thickness of ice or wet snow accumulation on a stay sheath. As with the UT Presence and State Sensor, the UT Optical Sensor was tested in both the laboratory and field settings. In the lab, the sensor was able to accurately determine the thickness of objects stuck onto the surface of an HDPE stay sheath specimen. The objects used were foam and had a known thickness. In the field, the UT Optical sensor was tested with both wet snow on a HDPE specimen and ice on a stainless steel VGCS sheathing specimen. In the wet snow experiments, the UT Optical Sensor determined the thickness of the accumulations with a 5% error, which is acceptable. In the icing experiments, the sensor
was able to determine the thickness of ice accumulations with a 10% error, which is also acceptable. The higher percent error was due to ice accumulations being much smaller than wet snow accumulations.

The experiments performed at the Scott Park experiment station not only verified that the UT Presence and State Sensor is ready for bridge deployment, but provided valuable observation regarding ice shedding. The first was the effect the solar radiation had on both the stay sheath and the ice layer. During both experiments, the solar radiation warmed the sheaths up significantly and caused the ice to melt through conduction and sublimate through heat radiation. The melting of the ice layer on the east and top of the stay sheath causes the center of gravity of the ice layer to continuously shift. This slightly rotates the ice layer towards the west side of the sheath. Since the weight of the ice is greater than the adhesion strength and the center of gravity is no longer directly above the center of the stay, separation begins to occur. The rotation and separation effect continues until the weight of the separated ice or another force, such as wind, is introduced causes the ice to shed.

Another new observation that can be made from the 2014-2015 winter experiments is that the interstice can completely dry out while ice is still present on the stay sheaths. This is caused by the solar radiation creating a greenhouse effect within the interstice by warming the stay sheaths to temperatures significantly above ambient air temperatures. Although the ice is still melting through heat radiation from the stay sheaths, the water travels along the ice on the inside of the interstice, rather than dropping onto the sheath and then rolling off the side. When this type of event occurs, the UT Presence and State Sensor reads 0 Volts, indicating the presence of air, which is
misleading. However, this can be avoided by using the entire sensor array to determine the presence of water and/or ice. For example, when this occurred in the outdoor experiment, the top and east indicated the presence of air, but the west and bottom were indicating the presence of water.

### 5.2 Future Work

There are five pieces of work that should to be continued in order to provide bridge owners and operators with the vital information that they need to make efficient and effective decision. The first is to slightly modify the design of the UT Presence and State Sensor. The current design still allows corrosion to take place on the copper strip terminals. Although these sensors are cheap to make, the foil tape suggested in Chapter 4 should be used to optimize the deployment time of each sensor. The foil tape has been used throughout the winter at the field station and shows no signs of corrosion. This tape is also conductive. The second piece that needs to be done is to perform a reliability study on the UT Presence and State Sensor. This should be done in the lab where numerous freeze thaw cycles can be repeated. The use of rain water during these reliability experiments is recommended. This would give the most accurate data considering the impurities of standard tap and bottled water are different than those in natural occurring rain water. The third piece to be continued is to evaluate array distribution, which can be done on one of the VGCS specimens at Scott Park. Currently an array of four UT Presence and State Sensors is being utilized to determine the presence and state of water on the sheath, however, the use of eight is recommended. This would allow the water presence in the interstice between the ice layer and sheath to
be tracked, which may eliminate help eliminate the problem encountered in the second field experiment where the interstice was dry and the top and east UT Presence and State Sensor gave misleading data. The fourth piece to success is to properly integrate the UT Presence and State Sensor and the UT Optical Sensor into the dashboard and implement it onto the VGCS. This will give bridge owners and operators the information they need to make their administrative decisions. The final piece to be considered is a shedding model. A shedding model that predicts ice or wet snow shedding off of stay sheaths would optimize lane closures by giving operations personnel a smaller window that ice fall is likely to happen.
References


Jones, K.F., (2010). Toledo weather conditions associated with ice accumulation on the Skyway Stays, Cold Regions Research and Engineering Laboratory, Hanover, NH 03755.


Appendix A

Data and Observations from the January 2015 Icing Event
DATE: 1-21-15  TIME: 2:55PM  STAYS 25°

Air Temperature: 27°

Current weather conditions: Lt. Snow - Flurries

Cable Conditions (choose): 24°  Clear [ ]  Ice Present [X]  Snow [ ]
Pylon Conditions (choose): 25°  Clear dry [ ]  Wet [X]  Snow cover [ ]
Roadway Conditions (choose): Clear dry [ ]  Wet [X]  Snow cover [ ]

Ice present on Leaf Wetness sensor (choose): Yes [ ]  No [ ]

Ice Thickness on stay:

Top : 1.35mm inches
East : 0.17mm inches
Bottom : ________ inches
West : ________ inches

Any additional comments:
Ice 1.35 mm on very top of cable. Thin layer on east side. 0.17 mm on pylon damp in spots
VGCS Event Feedback Form

DATE: 1-21-15  TIME: 6:40 PM

Air Temperature: 25°

Current weather conditions: Cloudy

Cable Conditions (choose): Clear [ ]  Ice Present [X]  Snow [ ]
Pylon Conditions (choose): Clear dry [ ]  Wet [X]  Snow cover [ ]
Roadway Conditions (choose): Clear dry [ ]  Wet [X]  Snow cover [ ]

Ice present on Leaf Wetness sensor (choose): Yes [ ]  No [ ]

Ice Thickness on stay:

Top: 1.85mm inches
East: 0.17 inches
Bottom: __________ inches
West: __________ inches

Any additional comments:
Ice 1.85mm on very top of cable. Thin layer on East side 0.17mm.
Pylon damp in spots.
Cable 22°.
Pylon 23°.
DATE: 2-4-15  
TIME: 4:00

Air Temperature: 33°

Current weather conditions: Snow

Cable Conditions (choose): Clear [ ]  Ice Present [ ]  Snow [-]
Pylon Conditions (choose): Clear dry [ ]  Wet [ ]  Snow cover [ ]
Roadway Conditions (choose): Clear dry [ ]  Wet [ ]  Snow cover

Ice present on Leaf Wetness sensor (choose): Yes [ ]  No [ ]

Ice Thickness on stay:

Top : ________ inches
East : ________ inches
Bottom : ________ inches
West : ________ inches

Any additional comments
LIGHT SNOW COVERING CABLES AT VERY BOTTOM FOR APROX. 15'
DATE: 2-4-15       TIME: 8:20 pm

Air Temperature: 26°

Current weather conditions: Clear

Cable Conditions (choose): Clear [ ]    Ice Present [ ]    Snow [x]
Pylon Conditions (choose): Clear dry [ ]    Wet [x]    Damp    Snow cover [ ]
Roadway Conditions (choose): Clear dry [ ]    Wet [x]    Snow cover [ ]

Ice present on Leaf Wetness sensor (choose): Yes [ ]    No [ ]

Ice Thickness on stay:
Top: _______ inches
East: _______ inches
Bottom: _______ inches
West: _______ inches

Any additional comments
Cables Southside clean
Cables Northside had light snow the first 15' cables was 24°
<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Air Temp</th>
<th>Current Weather Conditions</th>
<th>Cable conditions</th>
<th>Pylon conditions</th>
<th>Roadway condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3/2015</td>
<td>6am</td>
<td>28</td>
<td>frez rain</td>
<td>Clear</td>
<td>X</td>
<td>X</td>
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<tr>
<td>1/3/2015</td>
<td>10:30am</td>
<td>31</td>
<td>frez rain</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>1/3/2015</td>
<td>7:45pm</td>
<td>37</td>
<td>rain</td>
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<td>8:15am</td>
<td>27</td>
<td>snow/freezing rain</td>
<td>0.31mm</td>
<td>21.5</td>
<td>X</td>
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<td>11:15am</td>
<td>27</td>
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<td>0.46mm</td>
<td>24</td>
<td>x</td>
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<tr>
<td>1/21/2015</td>
<td>2:55pm</td>
<td>27</td>
<td>Lt snow - Flurries</td>
<td>Top 1.35mm</td>
<td>24</td>
<td>x</td>
</tr>
<tr>
<td>1/21/2015</td>
<td>6:40pm</td>
<td>25</td>
<td>Cloudy</td>
<td>Top 1.85mm</td>
<td>22</td>
<td>X</td>
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<tr>
<td>2/3/2015</td>
<td>7:30am</td>
<td>2</td>
<td>Flurries</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
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<td>4:15am</td>
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<td>Flurries</td>
<td>x</td>
<td>x</td>
<td>X</td>
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<td>2/4/2015</td>
<td>1:30pm</td>
<td>34</td>
<td>Snow</td>
<td>X</td>
<td>x</td>
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<tr>
<td>2/4/2015</td>
<td>4:00pm</td>
<td>33</td>
<td>Snow</td>
<td>X</td>
<td>29</td>
<td>Damp In spots</td>
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<tr>
<td>2/4/2015</td>
<td>8:20pm</td>
<td>26</td>
<td>Clear</td>
<td>X</td>
<td>24</td>
<td>Damp In spots</td>
</tr>
</tbody>
</table>

VGCS Winter condition report

Matt Harvey
Shift Manager
1/21/2015

Date