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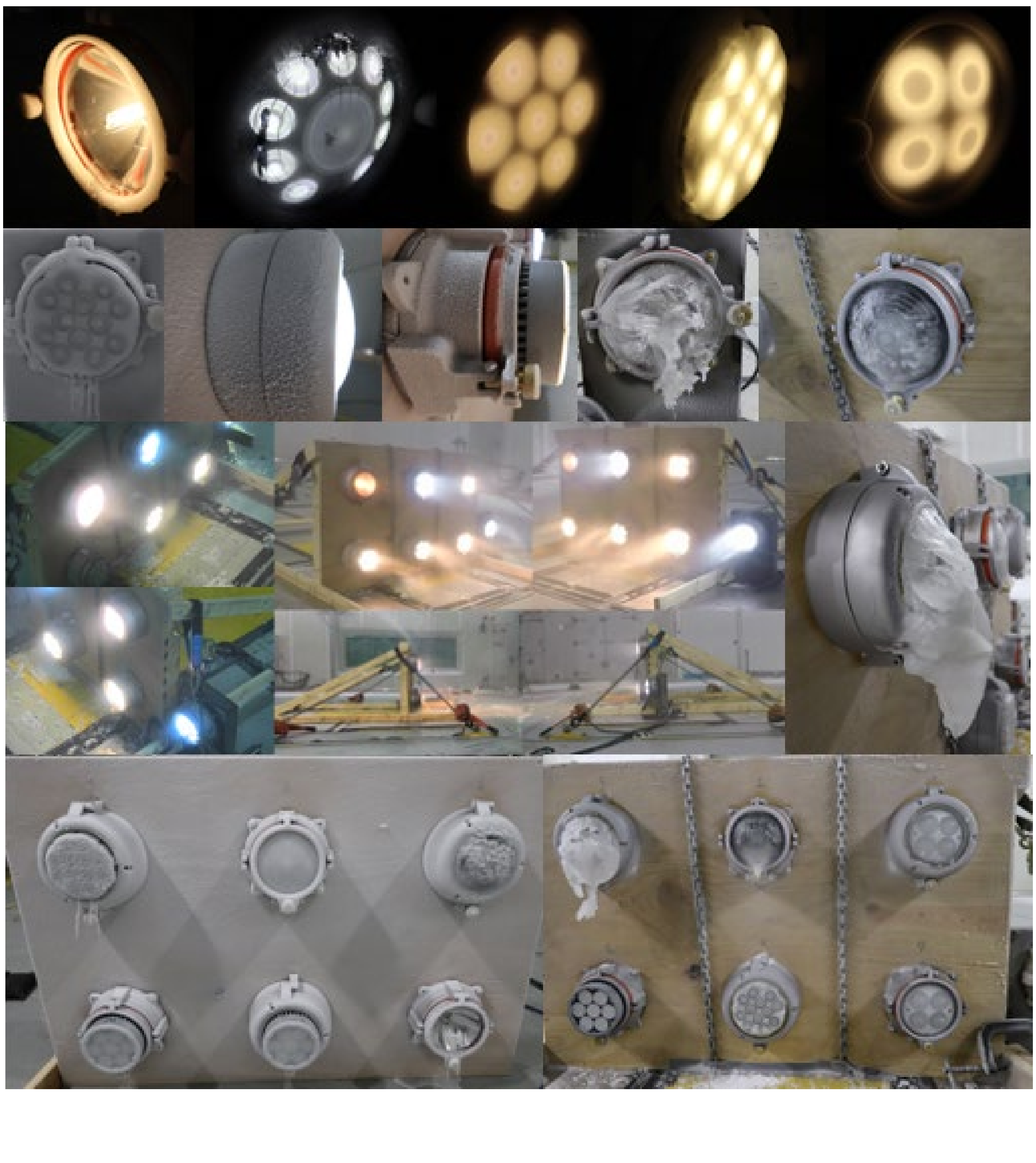
Compliance Testing for Locomotive LED Headlights and Auxiliary Lights, Phase IV



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This report describes the work performed during Phase IV compliance testing of light-emitting diode (LED) fixtures used as locomotive headlights and auxiliary lights. The purpose was to study the performance of the lamps under severe cold weather conditions. Researchers sought to determine whether LED lamps could melt a 1/4-inch-thick layer of ice from a lens surface and whether the lamps would accumulate a coating of snow and ice when operated in the presence of very cold, windblown snow. Throughout the testing, halogen lamps, currently standard equipment on freight locomotives, were used as a performance benchmark.

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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

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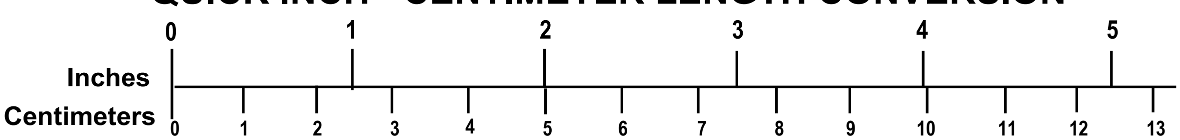

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

This report describes the test program used to study the performance of light-emitting diode (LED) fixtures used as locomotive headlights and auxiliary lights lamps under severe cold weather conditions. Researchers sought to determine whether LED lamps could melt a 1/4-inch-thick layer of ice from the lens surface and whether the lamps would accumulate a coating of snow and ice when operated in the presence of very cold, windblown snow. Throughout the testing, halogen lamps, currently standard equipment on freight locomotives, were used as a performance benchmark.

Over the last several years, the railroad industry has begun to introduce LED lighting, a relatively new technology, for locomotive headlights and auxiliary lights. In response to this initiative the Association of American Railroads (AAR) Locomotive Committee Headlight-Auxiliary Light Standard Technical Advisory Group has been leading efforts to evaluate the performance and illumination characteristics of LED lamps, particularly in comparison to their halogen counterparts that have historically been used on locomotives. To support the industry's initiative, the Federal Railroad Administration's Office of Research, Development, and Technology supported the development of a comprehensive four-phase research and test program in cooperation with the AAR to evaluate the performance of LED lamps in a railroad environment. In Phase I of this program, test procedures were established and tests were conducted to determine that currently available LED lamps satisfied applicable regulatory requirements and illumination characteristics under laboratory conditions. Subsequently, subjective assessment of the visibility aspects of LED lamps was evaluated under static (Phase II) and dynamic field (Phase III) test conditions, with halogen lamps used as a performance benchmark. The purpose of Phase IV testing was the evaluation of the performance of LED lamp samples under severe winter conditions using environmentally controlled laboratory facilities.

LED and halogen lamp samples from previous phases of this research were tested again during this study. During the Ice Melt Tests, the research team tested the lamp samples by measuring their ability to melt a 1/4-inch layer of accumulated ice on the lens while operating at a very low temperature. The team assessed lamp samples during the Snow Accumulation Test to determine their ability to prevent snow and ice from accumulating on the exposed surfaces while operating in at low temperatures.

The Ice Melt Test revealed that all the halogen lamps tested could completely melt the 1/4-inch layer of ice. The melting process started within 2 minutes of being powered on, and the ice layer was completely eliminated in under 10 minutes. In contrast, none of the LED samples could completely melt the layer of ice. Initial trials were conducted at -40 °C, and subsequently at -20 °C, to better understand the limits of the defrosting performance of the LED lamps. Some LED samples did exhibit partial melting of the ice, either through partial separation of the ice from the lens face, a flurry-like structure on the outer layer of ice, or the formation of icicles on the lamp housing. Researchers observed after trials at -20 °C that the ice layer on some LED samples had weakened, and striking the lamps with moderate force caused the layer of ice to fall from the face of the lamps, suggesting that the typical vibration generated by the moving locomotive could assist in defrosting the lamps during particular harsh winter conditions.

The results of the Snow Accumulation Test demonstrated that in the presence of cold, high-speed winds, the halogen lamps consistently accumulated ice on the fixture within 10 minutes of operation. Following each of three trials, an ice dome had formed on the housing of the halogen lamps, protruding several inches in front of the fixture. In contrast, the LED lamp samples accumulated very little ice, requiring close examination in order to detect and measure the thickness of ice. The ice layers formed on the LED samples varied in thickness, from nearly imperceptible up to approximately 1/4-inch.

This particular phase of the LED compliance testing efforts revealed several relevant observations related to the lamps' severe cold weather performance characteristics. The halogen lamps were more successful at melting an existing layer of ice on the lens, compared to the LED lamps. However, when tested in windy, snowy conditions, the LED lamps exhibited less accumulated ice in comparison to the halogen lamps, which formed larges domes of ice protruding several inches from the lens. These results provide a better understanding of how each of these lamp types might perform under severe winter conditions, but also demonstrate that for the questions studied here, there is not a unequivocal answer as to which is the better choice of lamp for winter use.

1. Introduction

This report summarizes Phase IV of the compliance testing of LED fixtures for use as locomotive headlights and auxiliary lights. This phase focused on evaluating the environmental performance of light-emitting diode (LED) lamps compared to halogen lamps in very cold and snowy conditions. This program was a collaborative effort between the Federal Railroad Administration's (FRA's) Office of Research, Development and Technology and the Association of American Railroads (AAR) Locomotive Committee's LED Headlight-Auxiliary Light Standard Technical Advisory Group (TAG).

Phase I of this undertaking addressed the photometric characteristics (e.g., luminous intensity and color temperature) of LED and halogen lamps, comparing their performance in a laboratory environment. Human-factors aspects related to visibility (e.g., track and wayside visibility, discomfort glare, and recognition of lamp patterns) of LED lamps were tested in static locomotive tests in Phase II and dynamic locomotive tests in Phase III.

1.1 Background

As part of Phase IV efforts to incorporate LED lamps into locomotive headlights, a research team comprised of Engineering Systems, Inc. (ESi) and ENSCO Rail, Inc. (ENSCO) designed two experiments intended to evaluate the performance of LED lamps during low-temperature environmental conditions. One experiment, referred to as the "Ice Melt Test," investigated the ability of LED and halogen lamps to melt a 1/4-inch layer of ice covering the exposed lamp and housing while operating under low-temperature conditions (-40 °C). A second experiment, referred to as the "Snow Accumulation Test," investigated whether LED and halogen lamps would accumulate snow and ice while operating in low-temperatures and wind speeds of 70 mph and 90 mph.

The experiments designed for this study incorporated testing guidance provided by the AAR TAG to simulate the worst case environmental condition likely to be encountered on the railway. The testing requirements proposed by the TAG committee were developed in accordance with AAR Standards S-5516[*] and S-9401.V1.0[†].

The following terms are used throughout this report:

1. **Lamp:** Assembly containing illuminating element(s) and a protective housing, using either halogen or LED technology.
2. **Housing:** Metal enclosure on the locomotive that allows lamps to be installed.
3. **Light fixture:** Combination of lamp and housing
4. **Test frame:** A structure used to mount several light fixtures in a specific orientation.

[*] LED Headlights and Auxiliary Lighting for Locomotives (2019); Section 3.7: Environmental.
[†] Railroad Electronics Environmental Requirements (2009); Table 3.1: Environmental Requirements (Vehicle Exterior Body Mounted).

1.2 Objectives

Based on the testing requirements established by AAR TAG, two primary objectives were established for Phase IV testing:

1. To determine the ability of lamps to melt 1/4-inch of accumulated ice after 30 minutes of operation at -40 °C.
2. To determine the ability of lamps to prevent ice and/or snow accumulation while being operated in low temperature (-40 °C) and high wind (up to 90 mph) conditions.

1.3 Overall Approach

To achieve the objectives described above, suitable test facilities were identified within the Automotive Centre for Excellence (ACE) laboratory at the University of Ontario Institute of Technology (Ontario Tech).[‡] The ACE laboratory has state-of-the-art climatic chambers capable of simulating a wide range of environmental conditions. The Ice Melt Test was performed at ACE's Small Climatic Chamber (SCC), which can maintain a temperature of -40 °C. The Snow Accumulation Test was performed at ACE's Climatic Wind Tunnel (CWT), which is also capable maintaining a temperature of -40 °C while generating wind speeds in excess of 155 mph (250 km/h). Additionally, the CWT has the capacity to inject moisture into the wind stream resulting in blowing rain or snow, depending on the temperature.

1.4 Scope

The controlled environmental chambers at ACE allowed researchers to simultaneously conduct multiple trials comparing LED and halogen lamp performance. The overall scope of the study was to compare LED and halogen lamps' ability to operate normally under various low-temperature environmental conditions.

1.5 Organization of the Report

The testing plan and requirements established by the AAR TAG are detailed in Section 2. Section 3 details the test methodology and specific protocols followed during both experiments. Analysis and discussion of the testing results is presented in Section 4. Finally, conclusions based on the entirety of the work are offered in Section 5.

[‡] https://ace.ontariotechu.ca/

2. Testing Plan and Requirements

The two experiments designed for this study followed the AAR TAG's testing requirements, which were developed in accordance with AAR Standards S-5516 (AAR, 2019) and S-9401.V1.0 (AAR, 2009). The requirements that guided the experimental design are specified below. Further details of the test methodology are discussed in Section 3.

2.1 TAG Testing Requirements

Each lamp sample shall be tested in each of the two primary types of housings. The following tests shall be performed in an environmental test chamber and shall be documented in real time with a video recording of the test.

1. **Ice Melt Test**
    a. The entire exposed, forward facing portion of the lamp shall be coated with 1/4-inch of ice. (The exposed portion does not include the back of the lamp nor does it include the side portion of the lamp that will be enclosed within the lamp housing.)
        i. The 1/4-inch layer of ice shall be formed on the exposed portion of the lamp, in one of the following ways, prior to initiating the test:
            1. The lamp may be submerged (and frozen) face-down in a container of water at a depth that will cause 1/4 inch of ice to form on the front and side portions of the lamp that would be exposed to the elements when installed in a lamp housing. A suitable container would be 1/2-inch larger than the diameter of the lamp.
            2. Water spray may be allowed to accumulate until a measurable 1/4-inch layer of ice is present on the front and sides of the lamp that would be exposed to the elements when installed in a lamp housing.

    b. The lamp shall be mounted in a locomotive headlamp housing and placed in an environmental test chamber (installed in the same orientation as it would be on the front of a locomotive) with an ambient temperature of -40 °C.

    c. Upon temperature stabilization of the light fixture at -40 °C, the lamp shall be powered with 74 VDC to simulate normal operation on the "bright" setting.

    d. Thirty minutes after power is applied to the lamp, the 74 VDC power supply shall be turned off and the presence of any residual ice accumulation shall be documented with photos, video, and measurement of any remaining ice. Special consideration shall be given to any ice that remains on the forward facing lens surfaces. A time-stamped video recording of the testing will show the exact timing of any melt-off events.

2. **Snow Accumulation Test**
    a. The lamp shall be mounted in a locomotive headlamp housing and placed in an environmental test chamber (installed in the same orientation as it would be on

the front of a locomotive) with an ambient temperature of approximately -7 °C. All samples were left soaking overnight at an ambient temperature of -20 °C to create the best conditions for facilitating icy build-up on the lamp sample.

b. Upon temperature stabilization of the lamp fixture at the desired temperature, a headwind of 70 mph shall be aimed directly at the lamp lens. Subsequent trials shall be conducted with a windspeed of 90 mph as well.

c. In combination with the headwind, a water spray shall be used to simulate a slushy/sticky/icy precipitation. The air temperature was kept at approximately -7 °C to create the best conditions for facilitating icy build-up on the lamp sample.

d. Upon start-up of the simulated headwind and precipitation, the lamp shall be powered with 74 VDC to simulate normal operation on the “bright” setting.

e. Over a period of 30 minutes, the lamp must monitored and any accumulation of precipitation on the lamp lens shall be recorded.

After each test, the lamps shall be evaluated on the amount of time required to melt the layer of ice, or the quantity of snow and ice that has accumulated on the lens of the lamp.

3. Methodology

This section presents the methods, testing apparatus, and analytical tools used in the Ice Melt Test and Snow Accumulation Test.

3.1 Lamp Samples

A randomly selected group of the lamp samples submitted to the researchers for Phase III testing were also used during Phase IV testing. The samples included four different LED lamp models provided by J.W. Speaker, Hydra-Tech, Railhead/Divvali, and SMART Light Source. The test samples also included two different halogen lamp models provided by AMGLO and ePowerRail. Eight samples per lamp model were provided to the research team to support Phases III and IV testing. Further details of the lamp models provided can be found in Appendix A.

3.2 Preliminary Testing and Setup

A major consideration during the experimental design was the establishment of a test fixture capable of holding multiple lamp housings simultaneously. Following discussions with ACE regarding wind loading and available anchor points within the environmental chambers, researchers constructed a wooden test frame with diagonal braces. They then built a pair of test fixtures – each fixture capable of holding up to 6 locomotive housings and lamps (see Figure 1). ACE approved the design specifications of the structures to withstand the high-wind, low-temperature and high-humidity conditions required for testing.

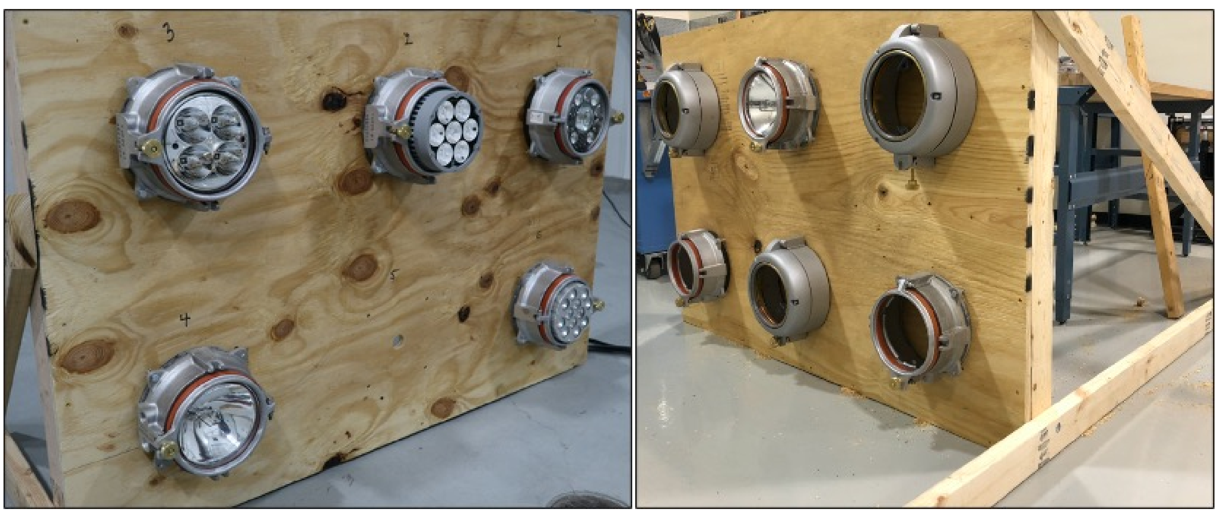


Figure 1. Test frames with light fixtures mounted

3.2.1 Preliminary Temperature Testing

One concern related to the test frame design was related to potential thermal interference between neighboring lamps, particularly for those lamps directly adjacent to a halogen lamp. To investigate whether the temperature of any given light fixture would affect another one, a simple test frame with five light fixtures was positioned outdoors at ambient temperatures between -17

°C and -15 °C (1.4 °F and 5 °F).[§] All five lamps were powered on to simulate operation in "bright" mode. After 30 minutes of operation, the temperature of the test frame and light fixtures was measured. Due to the low thermal conductivity of wood, these measurements showed no significant increase in temperature of the test frame in areas surrounding each light fixture.

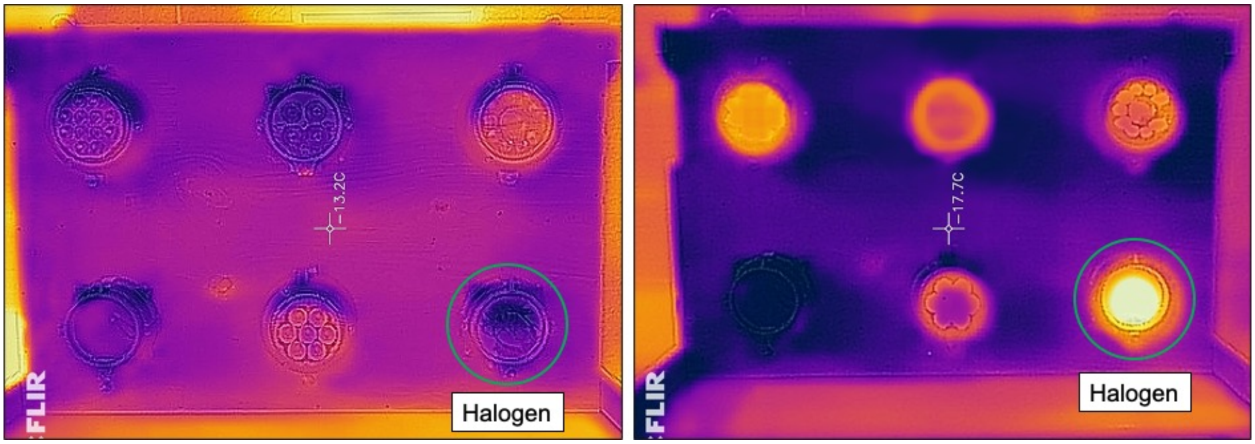


Figure 2. Thermal image of preliminary temperature testing

A second concern related to the test frame design was the material selected. The low thermal conductivity of wood prevented any of the lamps' operating temperature from being influenced by adjacent lamps. Conversely, there were concerns that the wooden test frame would insulate the lamps, preventing the dissipation of heat into the typical metal body of a locomotive. To test for this potential effect, researchers built a metal test frame to house a single light fixture (see Figure 3). The preliminary temperature test described above was repeated with the addition of the metal test frame. They positioned the wood and metal test frames outdoors at similar ambient temperatures. They then evaluated the metal test frame with both halogen and LED lamps. The temperature of the lamp housings on both test frames were measured and found to be very similar. This result suggests that the wooden test frame did not insulate or otherwise influence the temperature of the light fixture any differently than a metal frame. To verify this conclusion, the metal frame with a single light fixture, alternately housing LED and halogen lamps, was included in the Ice Melt Test and the Snow Accumulation Test.

[§] These preliminary tests were performed during wintertime in Michigan.

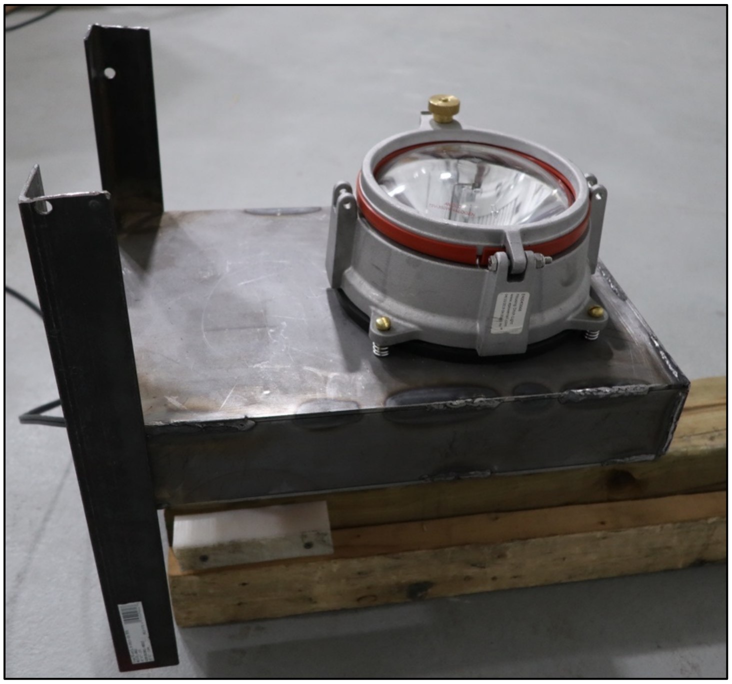


Figure 3. Metal test frame with housing and halogen lamp mounted

For all test iterations, the lamps were powered by a programmable DC power supply set to 75 VDC (BK Precision 9206; see Appendix E for datasheet).

3.3 Testing Facilities

Several facilities were considered for the environmental testing described above; however, only the ACE laboratory satisfied all of the requirements established by the TAG committee. The ACE laboratory is located on the main campus of Ontario Tech in Oshawa, Ontario (see Appendix F for fact sheet and specifications) and houses a total of five testing chambers with distinct capabilities. For the completion of the tests included in the present study, the Small Climatic Chamber (SCC) and the Climatic Wind Tunnel (CWT) were used.

3.3.1 Small Climatic Chamber

The SCC is large enough to fit two sedan cars. It can maintain temperatures as low as -40 °C and humidity levels ranging from 5 percent to 95 percent relative humidity (RH). Additionally, the SCC can modify these environmental variables in a fairly short amount of time, minimizing the time required between test iterations.

3.3.2 Climatic Wind Tunnel (CWT)

The CWT is a large testing chamber typically used to test objects from small cars to trucks and buses. It can generate wind speeds in excess of 155 mph (250 km/h) while maintaining temperatures as low as -40 °C and humidity levels from 5 percent to 95 percent RH. Anchors are located at various points on the floor allowing for secure attachment of the test frames.

3.4 Ice Melt Test

Researchers conducted the Ice Melt Test in the SCC on January 6, 2020. They installed the lamp samples onto the test frames inside the chamber for 4 to 5 hours prior to testing in order to reach a stable temperature of -40 °C. Once the samples' temperature had stabilized, they laid the test frames horizontally on a level, flat floor. They repeatedly sprayed the lamp samples with a thin coating of water until the desired 1/4-inch layer of ice formed on the exposed surfaces (see Figure 4 and Figure 5).

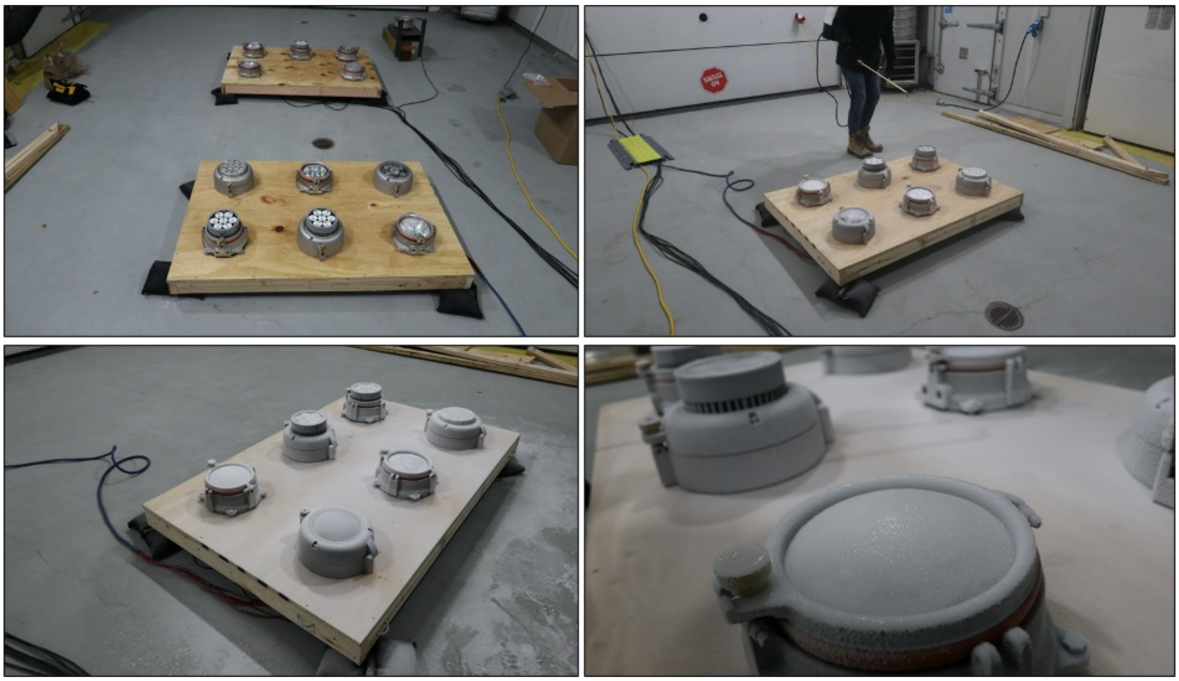


Figure 4. Setup of light fixtures in the SCC for ice layering

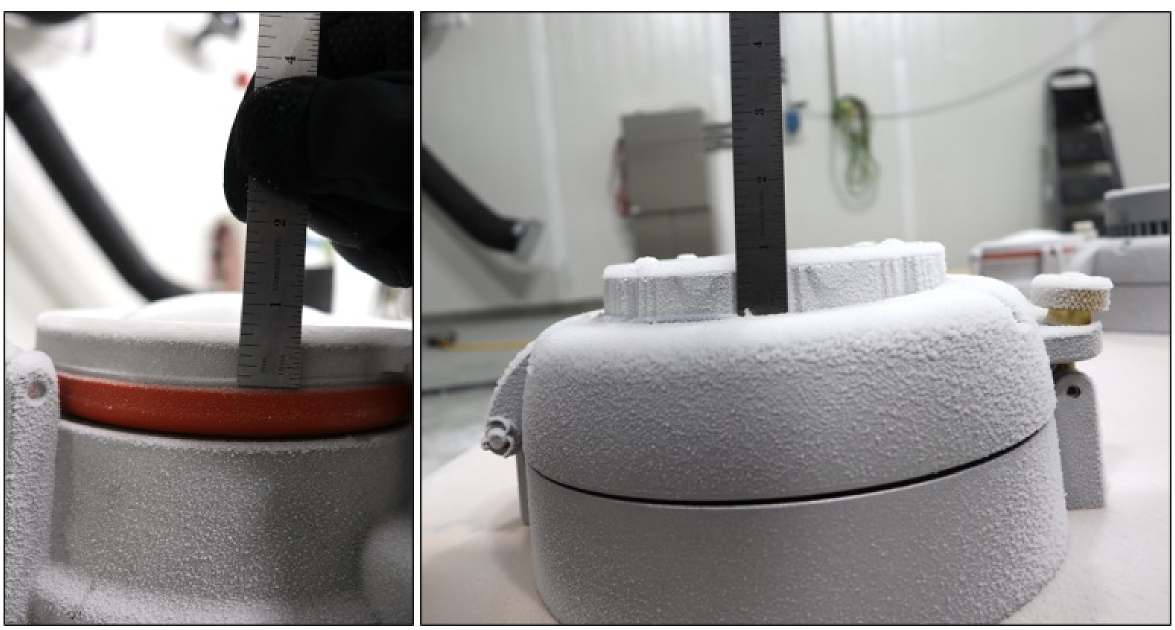


Figure 5. Light fixtures with 1/4-inch accumulation of ice

The frequent opening and closing of the SCC to allow for the researchers to spray water onto the lamps resulted in a 2 to 3 degree increase in the ambient temperature. Prior to the start of each trial, the SCC temperature was allowed to stabilize between -38 °C and -40 °C. For each trial, up to nine lamps were powered simultaneously with 74 VDC. After 30 minutes of operation, the presence of any residual ice was documented with photos, video, and measurements of area and thickness. This test procedure was repeated for a total of five trials in order to test all the lamp samples. Based on the temperatures measured during the preliminary stages, researchers hypothesized that none of the LED samples would melt any ice after 30 minutes of operation. Therefore, they gathered measurements for the second trial after a continuation of the first 30 minutes of operation, letting the samples operate for a full hour. The third trial was another evaluation of the lamps after 30 minutes of operation at -40 °C, but with a different, randomized placement of the lamp samples compared to the first trial. The fourth and fifth trials were designed to evaluate the residual ice on the lamp samples after 30 minutes of operation at -20 °C. For Trials 1 and 3, the placement of the lamp samples within the testing frame was randomized. Selected photographs of the Ice Melt Test are provided in Appendix B.

3.5 Snow Accumulation Test

Following the Ice Melt Test, researchers completed the Snow Accumulation Test on January 7, 2020, using one of the wooden test frames and the metal test frame. Photographs taken during the Snow Accumulation Test are provided in Appendix C. The test frames were securely chained to the floor of the CWT in order to withstand the expected wind loading. Following the recommendations of ACE test personnel, an ambient temperature of -20 °C to -15 °C was the ideal temperature for creation of wet, sticky snow that would be likely to stick to the lamps. All lamp samples were left in the CWT overnight to stabilize at temperatures between -20 °C and -15 °C.

Figure 6. Test frame installed in the CWT prior to Snow Accumulation Test

After allowing the lamps' temperature to stabilize overnight, researchers increased the ambient temperature of the CWT to approximately -7 °C. The slightly higher temperature allowed for the production of snow with "packing" characteristics, or snow that could more easily accumulate on the lamp surfaces. The research team sought this type of snow to simulate the worst-case conditions in which the lamps would likely be used.

The experimental design for this test included three trials. For each trial, the team tested a different set of lamps and randomly selected their position within the testing frames. The first two trials were conducted with wind speeds of approximately 70 mph (113 km/h). The last trial was conducted with wind speeds of approximately 90 mph (145 km/h). During all trials, all lamps were powered with 75 VDC to simulate "bright" mode operation for 30 minutes. After this period, any accumulation of precipitation was documented via photographs, videos, and measurements. The thickness of ice present was measured using a digital caliper, a two-sided steel ruler, and a depth gauge.

4. Results and Discussion

This section presents a summary Phase IV testing results as well as an explanation of the analysis employed and discussion of the implications.

4.1 Ice Melt Test Results

After researchers had applied the desired 1/4-inch thick layer of ice, they rotated the test frames so that the light fixtures were aimed parallel to the ground, replicating the typical orientation when installed on a locomotive. Three separate frames were used to test multiple samples simultaneously. The three test frames were positioned in a way that none of the lamps would project light directly onto another lamp (see Figure 7). This precaution was taken to avoid a scenario where light projected onto a lamp may expedite melting of the ice.

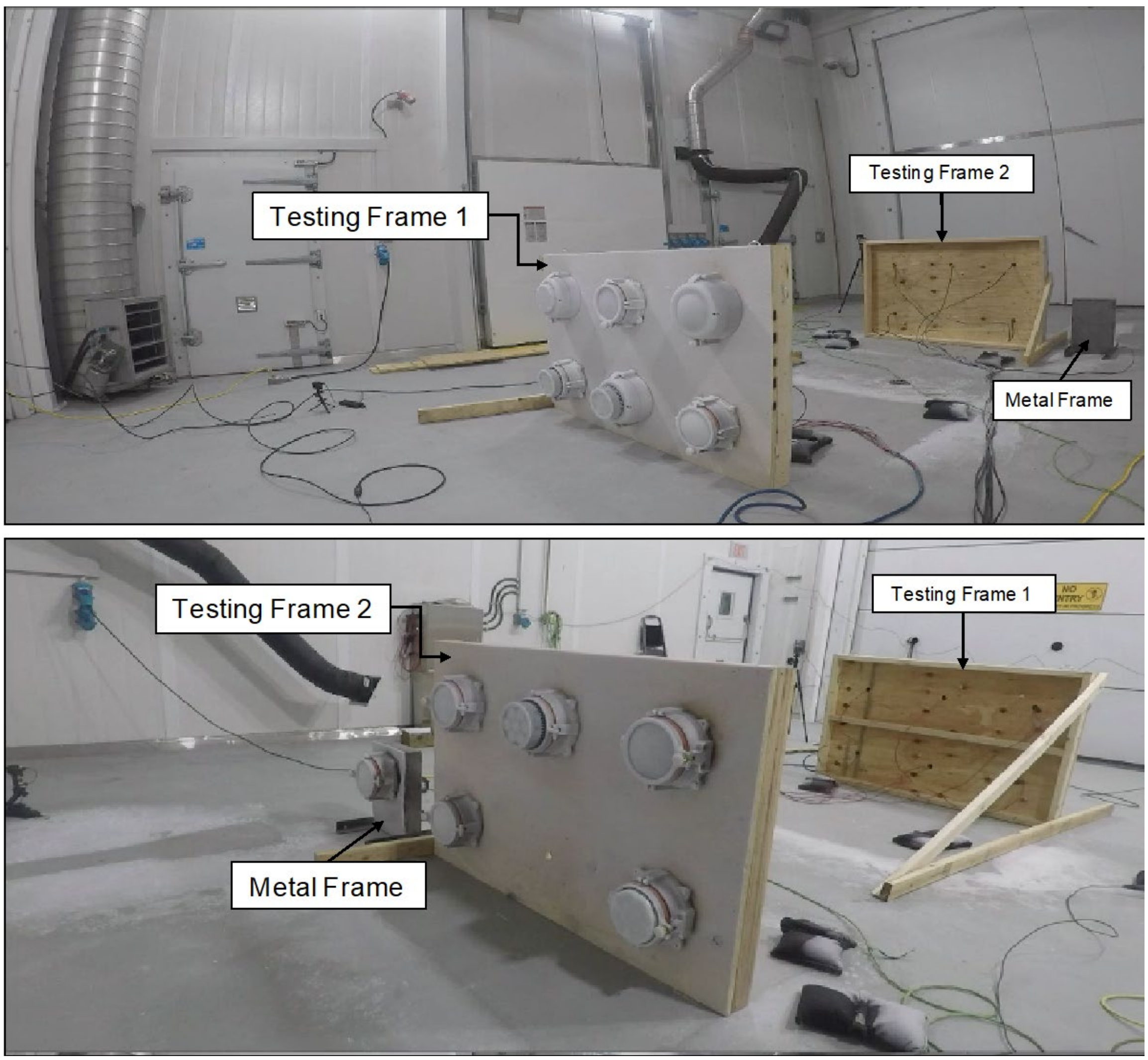


Figure 7. Setup of test frames in the SCC

During the Ice Melt Test, five 30-minute trials were completed. In each trial, up to nine lamp samples were tested. The original test plan included a single 30-minute trial for each group of lamps. Based on discussions with the AAR TAG and FRA during the test planning, researchers expected that this length of time would be sufficient to allow the lamps to melt the 1/4-inch layer of ice. Following the first trial, no ice melting was observed on any of the LED samples. However, both halogen lamps used in this trial melted all ice from the lens surfaces within 6 to 7 minutes. Following this initial trial, the researchers modified the test plan by extending the planned 30-minute trials to 1 hour, in order to determine if a longer period of time would facilitate defrosting of the LED lamps.

Table 1. Summary of Ice Melt Test trials

Trial #	Duration (minutes)	Ambient Temperature (°C)	Comments
1	30	-40 °C	
2	30	-40 °C	Extension of Trial 1
3	30	-40 °C	
4	30	-20 °C	Same lamps as Trial 3
5	30	-20 °C	Extension of Trial 4

4.1.1 Trial 1

For the first trial of the Ice Melt Test, nine lamp samples were evaluated, consisting of seven LED lamps and two halogen lamps. The average temperature in the SCC during this trial was -38.5 °C; the RH varied between 60 percent and 80 percent. During the first trial, only the two halogen samples exhibited melting of the ice layer, which was completely melted from both samples in less than 7 minutes (see Table 2). Figure 8 shows that after 30 minutes, the ice remained on all LED samples in this trial, while the halogen samples were completely free of ice.

Table 2. Ice Melt Test, Trial 1 – temperature -40 °C

Lamp No.	Test Frame	Lamp Code	Melting Event?	Time of Event (minutes)	Comment
1	1	LED 3	No	-	
2	1	LED 1	No	-	
3	1	LED 2	No	-	
4	1	LED 4	No	-	
5	1	Halogen 1	Yes	< 7	The melting process started within 2 minutes of operation.
6	2	LED 2	No	-	
7	2	LED 4	No	-	
8	2	LED 1	No	-	
9	Metal	Halogen 1	Yes	< 6	The melting process started within 2 minutes of operation.

4.1.2 Trial 2

Following Trial 1 in which none of the LED lamps exhibited any evidence of defrosting after the first 30 minutes of operation, researchers modified the test plan by adding an additional 30 minutes of operation with the same lamp samples and temperature. The average temperature during Trial 2 was again -38.5 °C, and RH varied between 60 percent and 80 percent. At the conclusion of this trial, and after a total of 60 minutes of operation, none of the LED samples could completely melt the ice from their lenses. However, two LED samples (both of the same model, LED 2) exhibited limited melting or some other change in the appearance of the ice layer. One sample partially melted the ice layer near the top of the lens (see orange circle in Figure 8), while the another sample produced a cluster of ice crystals over the outer layer of ice covering the lens (see yellow circle in Figure 8; the gray circles denote lamps that were not powered during this trial).

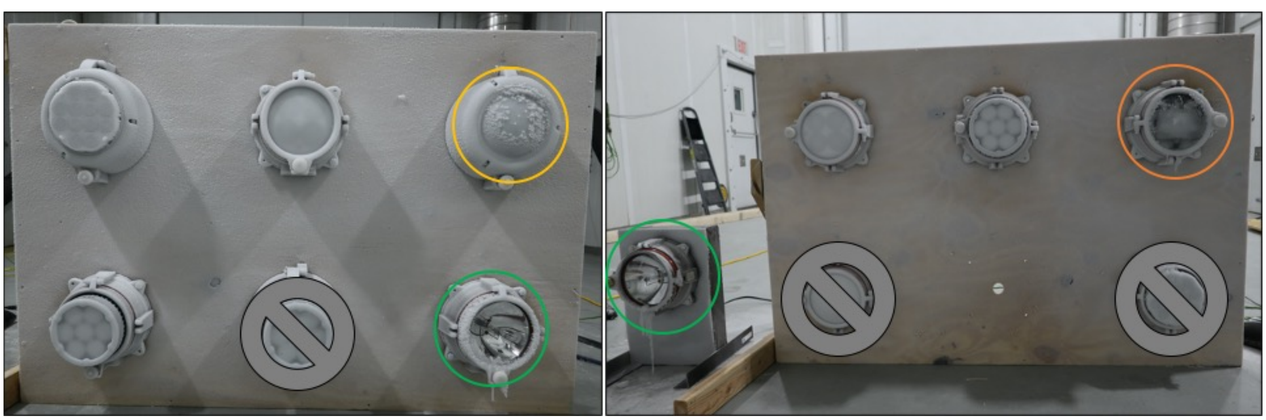


Figure 8. Extent of ice melting at the conclusion of Trial 2

4.1.3 Trial 3

For Trial 3, a different combination of nine lamp samples were tested, consisting of seven LED lamps and two halogen lamps. The average temperature during this trial was -39.3 °C; RH was between 60 percent and 80 percent. Consistent with the Trial 1 observations, after 30 minutes of operation in “bright” mode, only the halogen lamp completely melted the layer of ice. The melting of the ice layer began within 2 minutes of being powered on and was completed in less than 8 minutes.

After 30 minutes of operation, no LED samples had completely melted the ice layer. However, two LED lamp models (three samples in total) exhibited partial melting of the ice or other signs of an interaction between the lamp’s heat and the layer of ice covering the lens. The two samples of LED 3 exhibited a partial separation of the layer of ice from the lens face of the lamps. In addition, one of the LED 3 samples developed icicles on the bottom portion of the light fixture, indicating ice had melted, dripped down, and refrozen. The LED 2 sample tested in Trial 3 developed a flurry-like structure on the outer layer of ice covering the lens, just as it had in Trial 2.

Table 3. Ice Melt Test, Trial 3 – temperature -40 °C

Lamp No.	Test Frame	Lamp Code	Melting Event?	Time of Event (minutes)	Comment
1	1	LED 3	Partial	-	Layer started separating from the lens face, and flurry-like structure on outer layer.
2	1	LED 1	No	-	
3	1	LED 2	Partial	-	Flurry-like structure on outer layer
4	1	LED 4	No	-	
5	1	LED 4	No	-	
6	2	LED 1	No	-	
7	2	LED 4	No	-	
8	2	Halogen 2	Yes	< 8	The melting process started within 2 minutes of operation.
9	Metal	LED 3	Partial	-	Icicle formations and separation of ice from the lens face

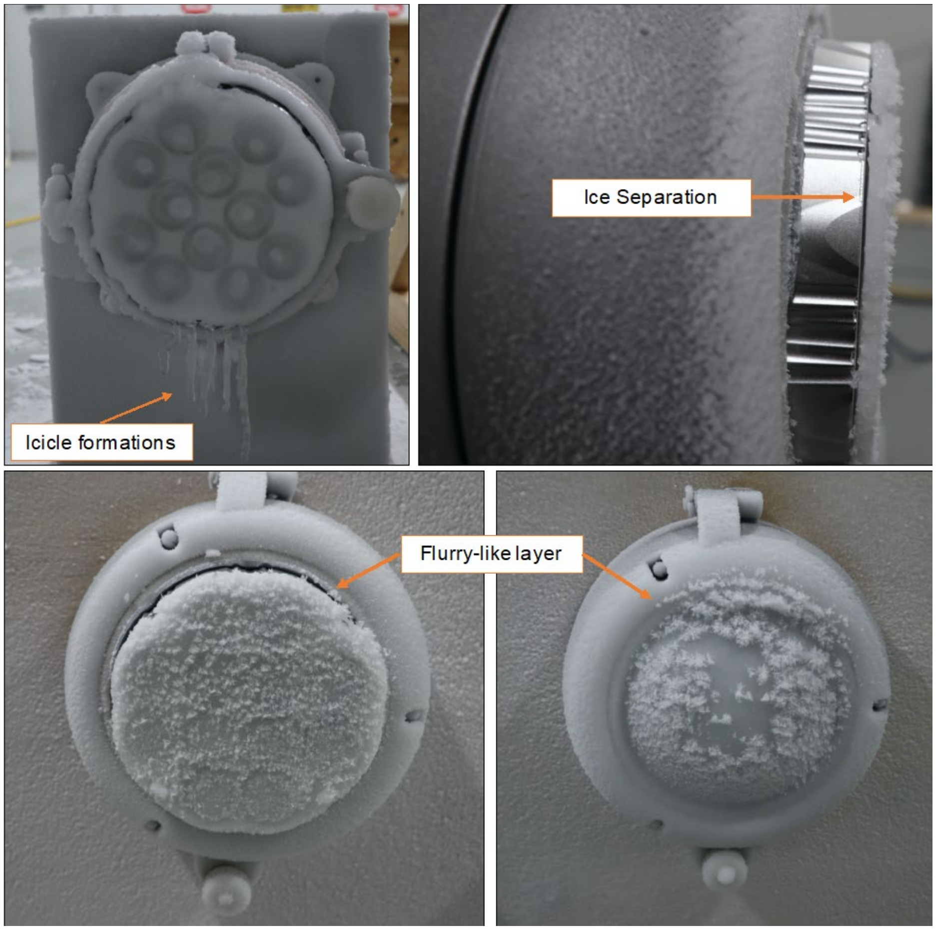


Figure 9. Light fixtures after Trial 3 and 30 minutes of operation

4.1.4 Trial 4

In Trial 4, researchers tested nine LED lamp samples. After the limited ice melting by LED samples in Trials 1–3, the average ambient temperature during Trial 4 was increased to -19.9 °C; average RH was measured at approximately 80 percent.

The LED samples were powered on and operated in "bright" mode for 30 minutes. Again, none of the LED lamps completely melted the ice layer. However, all LED lamp models tested, other than LED 1, showed some change in the appearance of ice layer. Table 4 shows the results of Trial 4 and describes the change in appearance of the ice that was observed.

Compared to the results exhibited in the prior trials, the partial melting produced by LED 2 were characterized by larger portions of the lens being free of ice. Samples of LED 3 developed larger icicle formations and the separation between the lens and the ice layer increased (see Figure 10). Samples of LED 4, which extended farthest beyond the lamp housing, melted ice into water droplets around the lateral portion of the lamp (see Figure 10).

Table 4. Ice Melt Test, Trial 4 – temperature -20 °C

Lamp No.	Test Frame	Lamp Code	Melting Event?	Time of Event (minutes)	Comment
1	1	LED 3	Partial	-	Layer started separating from the lens face, and flurry-like structure on outer layer.
2	1	LED 1	No	-	
3	1	LED 2	Partial	-	Flurry-like structure on outer layer
4	1	LED 4	-	-	Water droplets around the lamp
5	1	LED 4	-	-	Water droplets around the lamp
6	2	LED 1	No	-	
7	2	LED 4	-	-	Water droplets around the lamp
8	2	LED 2	Partial	-	Partial melt on the lens face
9	Metal	LED 3	Partial	-	Longer icicle formations and separation of ice from the lens face

Figure 10. LED light fixtures after 30 minutes of operation at -20 °C

4.1.5 Trial 5

Following the incomplete melting of ice documented in Trial 4, researchers performed an additional 30-minute trial at a temperature of -20 °C as an exploratory exercise. The goal of this trial was to evaluate if the thermal interaction between the lamp and the layer of ice would result in greater melting with the increased time. After this additional 30 minutes, they found no visible differences in the appearance of the ice. However, after powering off the lamps and documenting the extent of remaining ice, they observed that several samples of all lamp models had weakened. Specifically, the ice contacting the lens had melted, leaving a small gap, although the ice layer was still attached to the lamp housing. When the housings of some lamp samples were intentionally struck with moderate force, the layer of ice fell from the lens face.

The separation of the ice layer from the lamp lens suggests that vibration could work in conjunction with the lamp's heat output to facilitate the removal of ice from the lamp lens. A locomotive in motion may produce enough vibration to shed any accumulation of ice on LED lamps. However, this would require the locomotive to begin track movements prior to the LED lamp being completely defrosted, resulting in slightly less light output from the obscured lamp. Note that these LED lamps required more than 30 minutes to weaken the ice layer enough to be dislodged by applying a moderate amount of force.

Figure 11. Layer of ice falling from lens face after moderately hitting the lamp housings

4.2 Snow Accumulation Test Results

For the Snow Accumulation Test, lamp samples were tested using one of the wooden test frames and the metal test frame, as shown in Figure 6. The test frames were positioned perpendicular to the direction of the airflow and the precipitation nozzle of the CWT (see Figure 12).

For the Snow Accumulation Test, researchers completed three separate 30-minute trials. Trials 1 and 2 were conducted at winds speeds of 70 mph (113 km/h) while Trial 3 was conducted at 90 mph (145 km/h). All trials were performed at similar ambient temperature (-7 °C) and RH (an average of 92 percent RH). During each trial, up to seven lamp samples were tested. A total of sixteen LED lamps and three halogen lamps were tested during the course of all three trials.

Figure 12. Test frames inside the CWT at wind speeds of 70 mph (113 km/h)

4.2.1 Trial 1

Trial 1 involved testing six LED lamps and one halogen lamp. During this trial, no visible accumulation of snow or ice was present on the LED lamps. Approximately 10 minutes into the testing, the halogen sample began accumulating ice near the bottom of the light fixture. After approximately 14 minutes of operation, the accumulation of ice on the halogen lamp became visible via the video cameras. Icicle formations were observed on the bottom of the light fixture, and a shroud of ice formed over the lamp lens (see Figure 13).

After 30 minutes of operation, all lamps were powered off and the presence of ice or snow on the lamps was documented. Table 5 presents the results of Trial 1. LED 1 and 4 accumulated less than 1/16-inch of ice or snow on the lens, while LEDs 2 and 3 accumulated layers between 1/8-inch and 1/4-inch thick. The layer of ice formed on LEDs 2 and 3 was not smooth or uniform, resulting in the range of thickness measurements. Figure 14 and Figure 15 show the accumulation of ice and snow on the light fixtures for Trial 1. As is seen in these figures, the accumulation of ice on the halogen sample was significant. No ice accumulated directly on the lens of the halogen lamp, but a significant dome of ice was formed over the lens and attached to the lamp housing.

Figure 13. Photo taken during Trial 1 with detail view of halogen lamp

Table 5. Accumulation of Snow Test, Trial 1 – 70 mph wind

Lamp No.	Test Frame	Lamp Code	Accumulation?	Thickness	Comment
1	1	LED 3	Yes	1/8 inch - 1/4 inch	
2	1	LED 2	Yes	1/8 inch - 1/4 inch	
3	1	LED 1	Yes	< 1/16 inch	
4	1	Halogen 1	Yes	*	Ice dome formed over the light fixture. The dome protruded more than 2 inches from the front of the fixture.
5	1	LED 4	Yes	< 1/16 inch	
6	1	LED 3	Yes	1/8 inch - 1/4 inch	
7	Metal	LED 4	Yes	-	Not enough accumulation to be measurable.

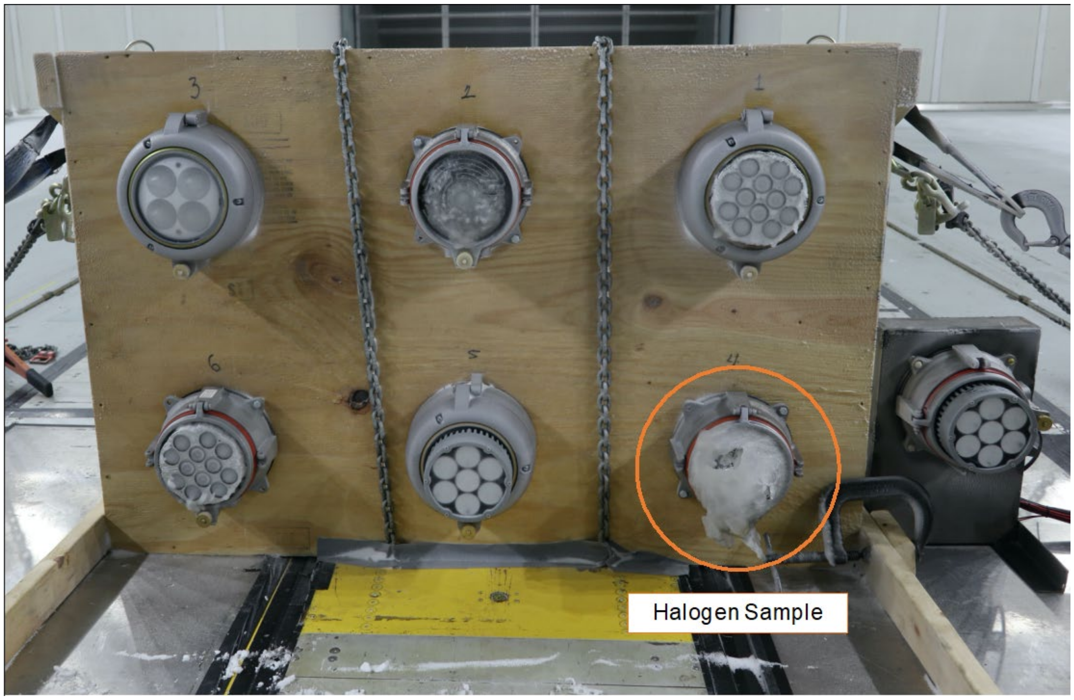


Figure 14. Accumulation of snow and ice on light fixtures after Trial 1

Figure 15. Close-up view of the accumulation of snow and ice on light fixtures after Trial 1

4.2.2 Trial 2

During Trial 2, researchers tested seven lamp samples. In contrast to Trial 1, the position of the halogen sample was predetermined to be on the upper row of the testing frame and in a different type of housing than used previously (see upper-left corner lamp in Figure 16).Other than the halogen sample, all other lamps were randomly positioned within the testing frames. Additionally, a non-powered LED sample was included in the bottom-left corner of the wooden test frame to establish a baseline for the amount of snow and ice accumulation expected on a non-operational LED. Similar to Trial 1, the results of Trial 2 showed that the halogen lamp developed a significant dome ice around the lamp. Table 6 contains observations and measurements made during Trial 2.

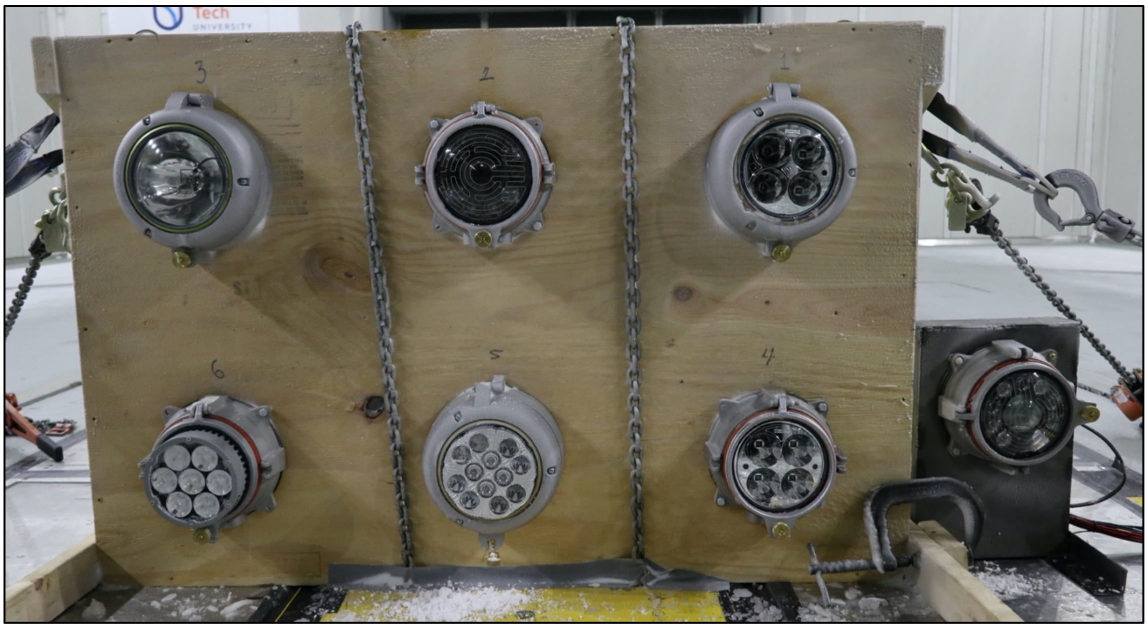


Figure 16. Setup of test frames and light fixtures for Trial 2

Table 6. Snow Accumulation Test, Trial 2 – 70 mph wind

Lamp No.	Test Frame	Lamp Code	Accumulation?	Thickness	Comment
1	1	LED 1	Yes	1/32 inch > 1/16 inch	
2	1	LED 2	Yes	1/8 inch - 1/4 inch	
3	1	Halogen 2	Yes	*	Ice dome formed around the light fixture. The dome protruded more than 3.5 inches from the front of the fixture.
4	1	LED 1	Yes	1/32 inch > 1/16 inch	
5	1	LED 3	Yes	1/8 inch - 1/4 inch	
6	1	LED 4	Yes	< 1/16 inch	Non-powered sample. Not enough accumulation to measure precisely.
7	Metal	LED 2	Yes	< 1/16 inch	Not enough accumulation to be precisely measurable.

During Trial 2, researchers observed an accumulation of ice on the halogen sample after less than 10 minutes of operation. Additionally, the amount of ice that had accumulated at the end of the trial was greater than what was observed during Trial 1. Figure 17 contains a photograph taken during Trial 2 after less than 15 minutes of operation. In the upper-left corner of this photograph, the circled lamp has an extended halo of emitted light compared to the other samples, indicating the accumulation of ice around the housing. In the bottom-right corner of the figure, portions of the icicle formations around the light fixture can be seen. Consistent with the results of Trial 1, the LED 2 and LED 3 samples accumulated the greatest amount of snow and ice, while LED 1 and LED 4[**] samples accumulated the least.

[**] LED 4 was not powered during this trial.

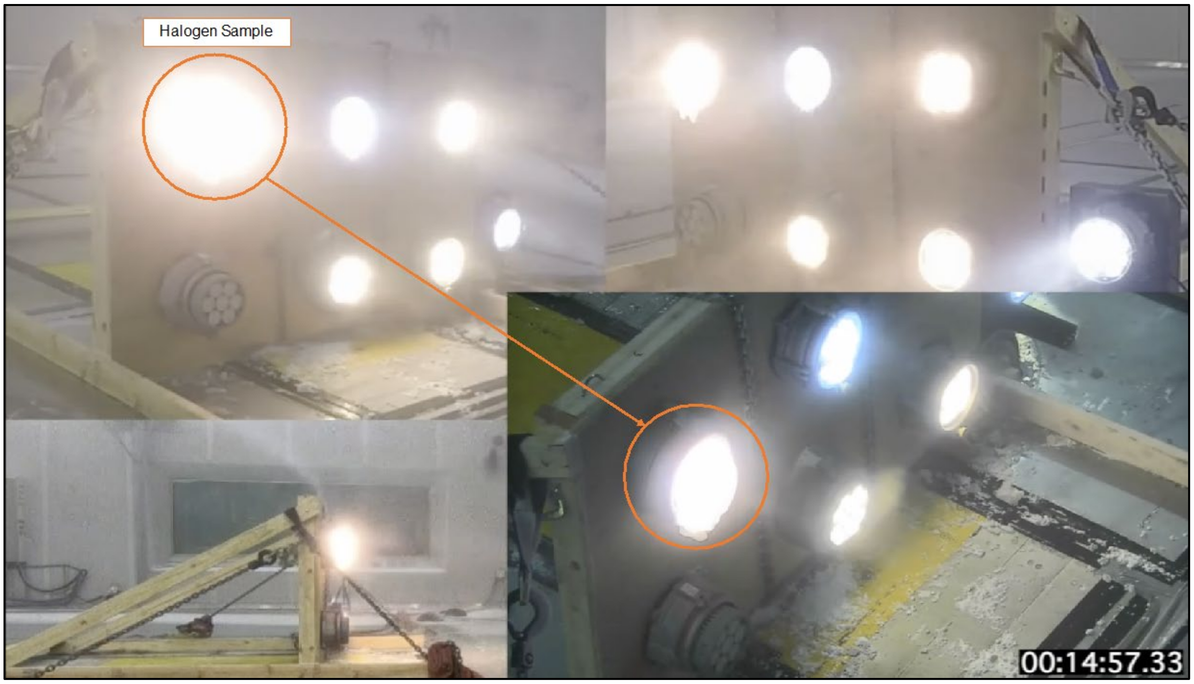


Figure 17. Photograph taken during Trial 2 showing ice accumulation on the halogen lamp

Figure 18 shows the accumulation of snow and ice on the light fixtures after completion of Trial 2. As shown in the upper-left corner of this figure, the extent of ice accumulation on the halogen sample was significantly greater than the accumulation on the LED samples. The dome of ice on the halogen sample extended beyond and below the front of the fixture more than 3.5 inches, while none of the LED samples exceeded 1/4-inch accumulation at the thickest portion measured.

A visual inspection of the non-powered LED 4 sample revealed that the accumulation of ice was not significantly different than the accumulation documented when LED 4 was powered during Trials 1 and 3. In all trials, the ice accumulation observed on LED 4 samples was less than 1/16-inch.

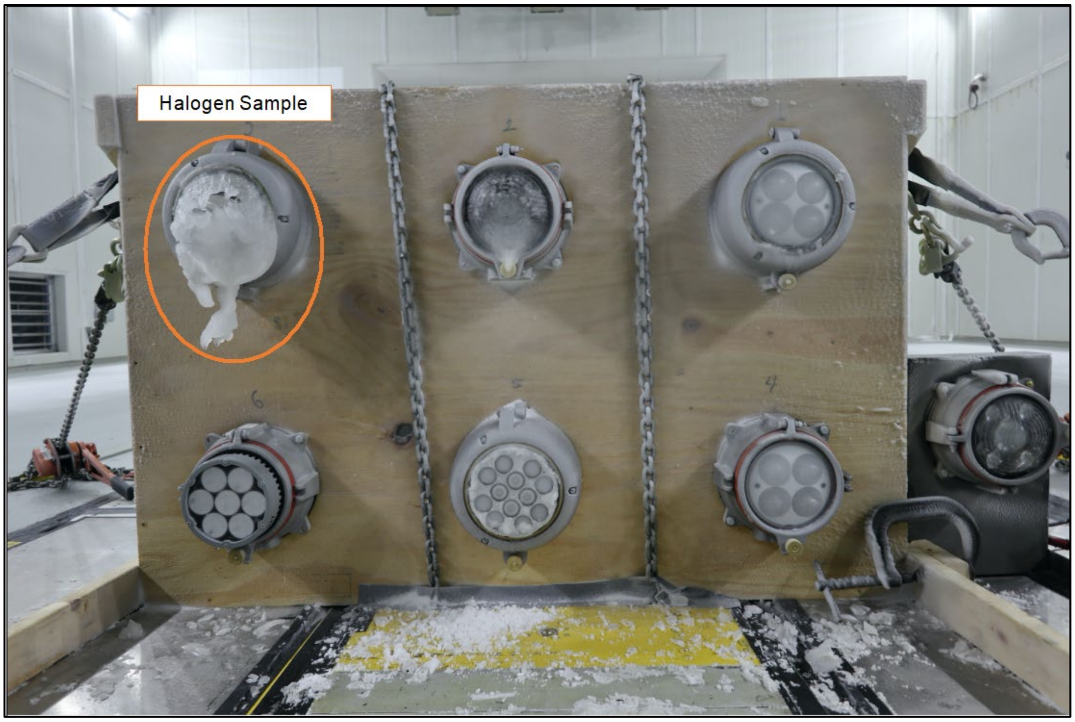


Figure 18. Accumulation of snow and ice on light fixtures after Trial 2

4.2.3 Trial 3

During Trial 3, all samples were randomly positioned within the wooden test frame while the halogen sample was installed in the metal test frame. A total of seven samples were tested, five LEDs and one halogen. This trial was conducted at wind speeds of approximately 90 mph (145 km/h).

The results observed during Trial 3 strongly correlated with results from previous trials; the halogen sample collected the greatest amount of snow and ice. Once more, after approximately 10 minutes of operation, there were visual indicators that the halogen sample was developing a dome of ice and an extended halo of light. The dome of ice covering the halogen light fixture at the end of the trial was not as pronounced as it had been after Trial 2, extending beyond the fixture approximately 2 inches. Similar to previous trials, the LED samples corresponding to models LED 2 and LED 3 accumulated the greatest amount of ice or snow directly on the lens, while models LED 1 and LED 2 accumulated the least amount of ice or snow. Table 7 shows the results of Trial 3 and the measured accumulation of snow and ice.

The increase in wind speed (from 70 mph to 90 mph) did not have a statistically significant effect on the total accumulation of snow or ice on the samples. Given the nature, purpose, and experimental design for this test, it was not possible to conclusively analyze the effect that wind speed may have on the accumulation of snow and ice.

Table 7. Snow Accumulation Test, Trial 3 – 90 mph wind

Lamp No.	Test Frame	Lamp Code	Accumulation?	Thickness	Comment
1	1	LED 3	Yes	1/8 inch - 1/4 inch	
2	1	LED 1	Yes	<1/8 inch	
3	1	LED 4	Yes	1/16 inch	
4	1	LED 4	Yes	1/16 inch	
5	1	LED 2	Yes	< 1/8 inch	
6	1	LED 4	Yes	< 1/16 inch	Non-powered sample
7	Metal	Halogen 1	Yes	*	Ice dome created around the light fixture. The dome protruded more than 3.5 inches from the front of the fixture.

Figure 19. Accumulation of snow and ice on light fixtures after Trial 3

4.3 Discussion of Ice Melt and Snow Accumulation Tests

For all Ice Melt trials conducted at -40 °C, the general trend observed was that the halogen lamps completely melted the 1/4-inch-thick layer of ice in under 30 minutes. None of the LED samples tested exhibited complete melting of the ice. However, the samples of model LED 2 and LED 3 did generate sufficient heat to weaken the bond between the ice and the lens. When the chamber temperature was increased to -20 °C, LED 2 and LED 3 exhibited greater weakening of this bond. In some samples, the layer of ice was slightly separated from the lens or portions of the layer were partially melted. This resulted in the ice layer being sufficiently weakened so that the ice broke loose from the housing with a moderate impact to the housing, suggesting that the vibration of a locomotive in motion may assist with defrosting the lamps. In other samples, icicles were produced toward the bottom of the light fixture, indicating a thaw and refreeze process had occurred. Finally, other samples formed flurry-like structures of snowflakes on the ice layer. In contrast, LED 1 and LED 4 did not exhibit signs of weakening or partial melting of the ice layers.

The Snow Accumulation Test revealed that the lamp models that exhibited a greater tendency to melt ice (i.e., Halogen 1, Halogen 2, LED 2 and LED 3) were also the models that accumulated the greatest amount of snow and ice. The halogen samples developed a significant dome of ice, which in most trials completely covered the lens. LED 2 and LED 3 accumulated a layer of ice on the lens; however, this accumulation was much thinner than what researchers observed on the halogen lamps. This result suggests a somewhat counterintuitive relationship between the lamp's heat output, the propensity to accumulate ice at high wind speeds and the ability to melt ice at low temperatures without the presence of wind. The samples that generated more heat (i.e., the halogen lamps) were more likely to defrost completely during the Ice Melt Test. However, these samples proved to accumulate greater amounts of snow and ice during the Snow Accumulation Test, with higher lamp temperatures corresponding to greater accumulation on the light fixture.

5. Conclusion

The Ice Melt Test revealed that in extreme low-temperatures of -40 °C, LED lamps could not melt a 1/4-inch-thick layer of ice. Additional trials of the Ice Melt Test performed at higher temperatures of -20 °C demonstrated limited, incomplete melting of the ice layer on LED lamps. Halogen lamps on the other hand performed very well in the Ice Melt Test. Multiple trials demonstrated these lamps produce sufficient heat to completely melt a 1/4-inch layer of ice at -40 °C.

The Snow Accumulation Test demonstrated that when exposed to high winds, low temperatures, and blowing snow conditions, LED lamps accumulated less ice on their lenses and around the lamp housings compared to halogen lamps. There was variation in the performance of the LED lamps tested, with models that have integrated defrost heaters accumulating more ice than those models without.

The implication of these findings should be carefully considered prior to implementing the use of LED lamps on road locomotives. The inability of LED lamps to melt ice at these extreme temperatures does not indicate this technology is unsuited for use in locomotives. Similarly, the potential for halogen lamps to accumulate considerable amounts of ice under low temperature, blowing snow conditions does not make them unfit for road service. Instead, these results provide insight regarding the performance of these lamps under adverse environmental conditions. Additionally, one consideration is the static nature of these tests conducted in a laboratory environment. When installed on a locomotive, these lamps are subjected to vibration that could affect the mechanics of snow falling on the lens, potentially impeding its accumulation or weakening its bond to the lamp. In addition, the presence of accumulated ice on the lens of the lamp would not render the lamp unusable. While a layer of ice on the lens does act as a filter, obscuring and dispersing the lamp's illumination, it does allow for the projection of a portion of its typical luminous intensity.

Future research should investigate two particular aspects that extend from the results of the present study. The first is the effect of locomotive vibration on ice accumulation and the ability of lamps to shed built-up ice. The second is the effect of different thicknesses of accumulated ice on the peak luminous intensity and photometric distribution of the LED lamps.

In summary, the current study revealed a somewhat unexpected contrast between the performance of halogen and LED lamps under two sets of controlled laboratory-induced environmental conditions. The halogen lamps were more successful in melting an existing layer of ice from the lens, whereas the LED lamps were unsuccessful in accomplishing this even after raising the ambient temperature in the test chamber. However, the LED lamps accumulated much less ice than the halogen lamps when operated in very cold and windy conditions. These results provide a better understanding of how each of these lamp types might perform under severe field service conditions, while also demonstrating that there is not an unequivocally better choice of lamp for severe cold weather conditions.

6. References

Association of American Railroads. (2009). AAR Manual of Standards and Recommended Practices Electronics Environmental Requirements and System Management. *Railroad Electronics Environmental Requirements Standard:* S-9401.V1.0.

Association of American Railroads. (2019). AAR Manual of Standards and Recommended Practices Locomotives and Locomotive Interchange Equipment. *LED Headlights and Auxiliary Lighting for Locomotives Standard:* S-5516.

Appendix A.
Lamp Samples

Figure 20. LED sample supplied by J.W. Speaker

Supplier: J.W. Speaker

Model: 554601

Specifications summary:

- Input voltage: 50–90 VDC
- Operating voltage: 75 VDC
- Current Draw: 1.25 A @ 50 VDC, 0.85 A @ 75 VDC, 0.70 A @ 90 VDC.
- Candela output: 200,000 cd min.
- Nominal LED color temperature: 5000 K

Figure 21. LED sample supplied by Hydra-Tech International

Supplier: Hydra-Tech International

Model: HYD-LOC001.28K (Hydra-Tech 2800 K)

Specifications summary:

- Wattage: 35 W
- Input voltage: 14–30 VDC
- Amp draw: 1.09 A @ 32 VDC
- 32-75 VDC Max brightness ditch light
- Output (cd): Exceeds 200,000 cd Requirement
- Color temperature: 2800 K

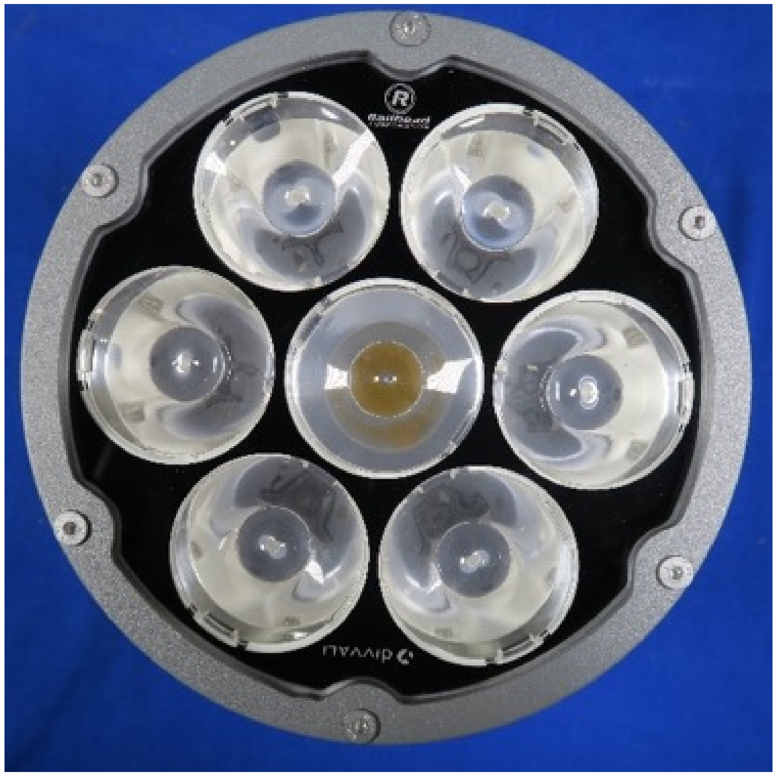


Figure 22. LED sample supplied by Railhead/Divvali

Supplier: Railhead/Divvali
Model: KE-PAR56 75V LED
Specifications summary:

- Wattage: 50 W
- Input voltage: 75 VDC
- CCT: 5500 K
- Candela: 174,000 cd
- 7½° off center brightness (2x the brightness)
- 20° beam cutoff

Figure 23. LED sample supplied by Smart Light Source Co.

Supplier: Smart Light Source Co.

Model: SLS-75VDC-60W-LED-PAR56

Specifications summary:

- Operating voltage: 75 VDC
- Rated wattage: 60 W
- Average bulb life: 50,000 hours
- Color temperature: 3000 K

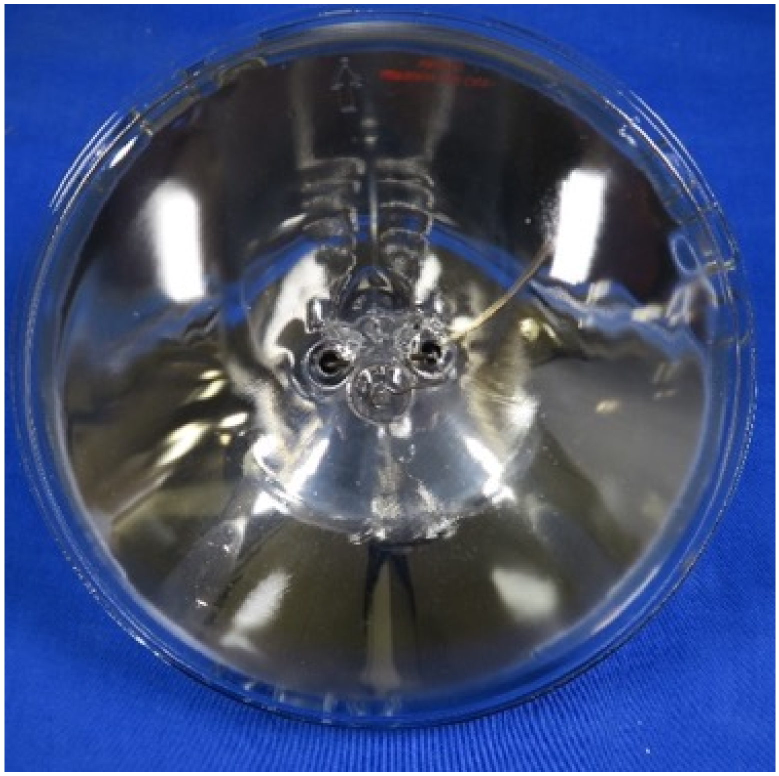


Figure 24. Halogen sample supplied by AMGLO

Supplier: AMGLO – Halogen Sample

Model: AHQV56-75V350WCS

Specifications summary:

- Design voltage: 75 VDC
- Design watts: 350 W
- Minimum candela: 200,000 cd
- Lab life: 2,000 hours

Figure 25. Halogen sample supplied by ePowerRail

Supplier: ePowerRail (SMART Light Source, Co.)

Model: FRA350PAR56-SP

Specifications summary:

- Average life: 4,000 hours
- Candela: 200,000 cd
- Wattage: 200 W
- Input voltage: 75VDC

Appendix B.
Ice Melt Test – Selected Photographs

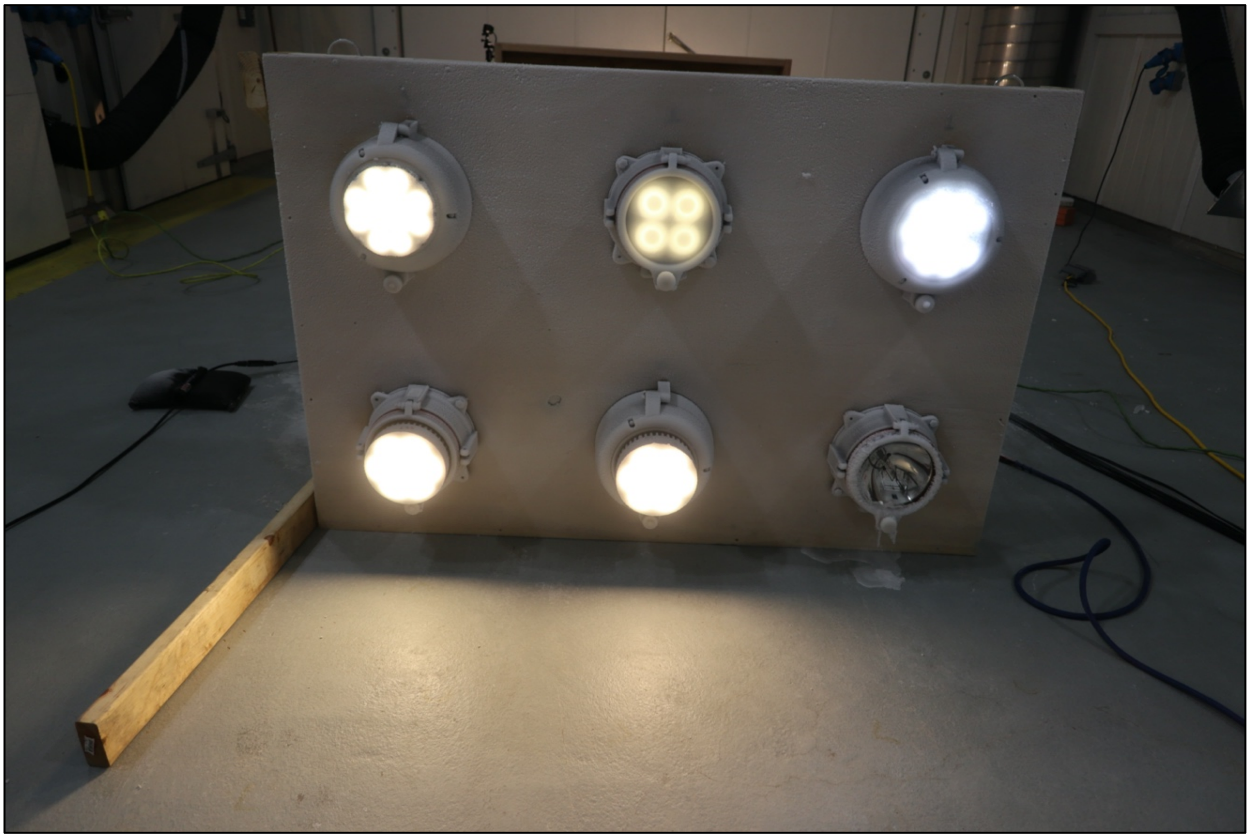


Figure 26. Test frame 1 with lamps powered on

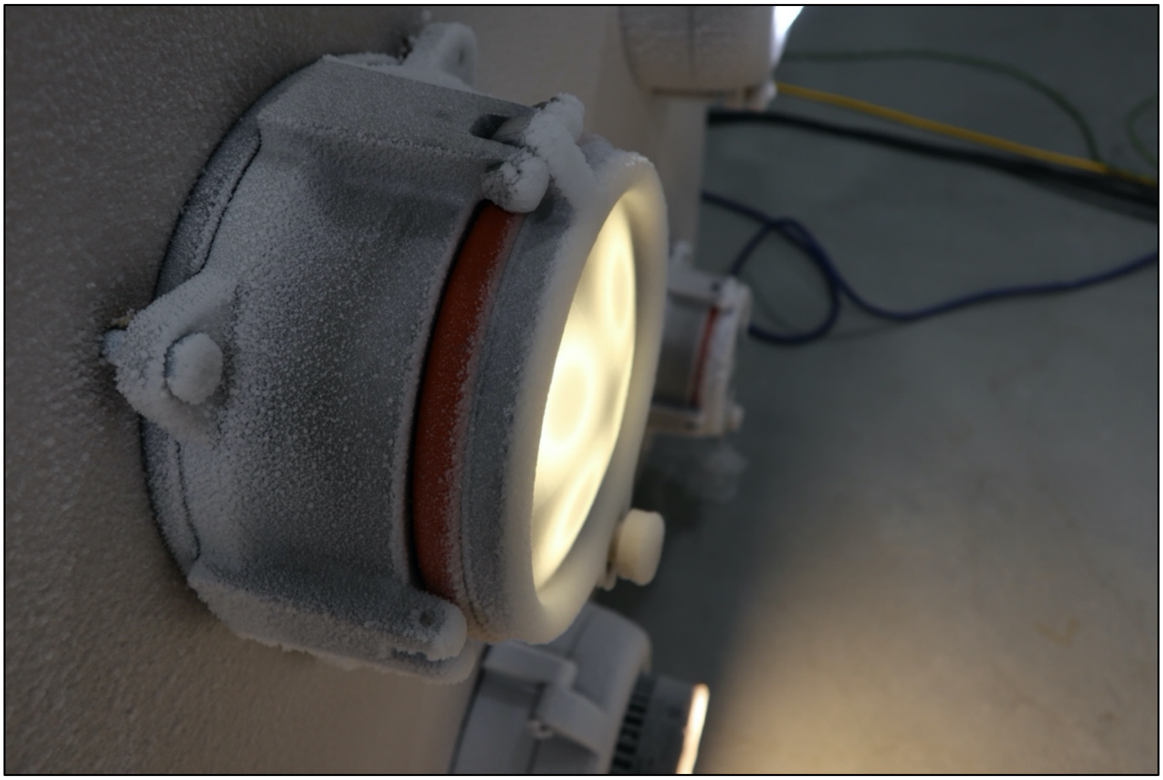


Figure 27. LED sample during testing

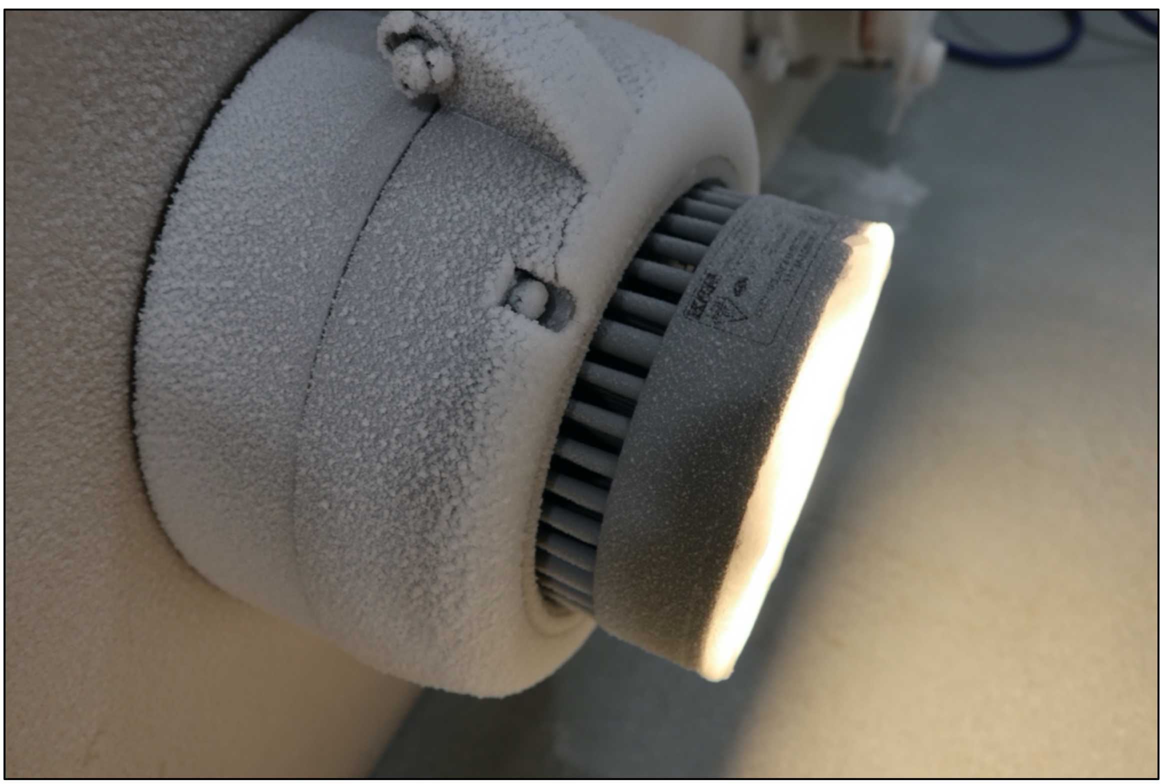


Figure 28. LED sample during testing

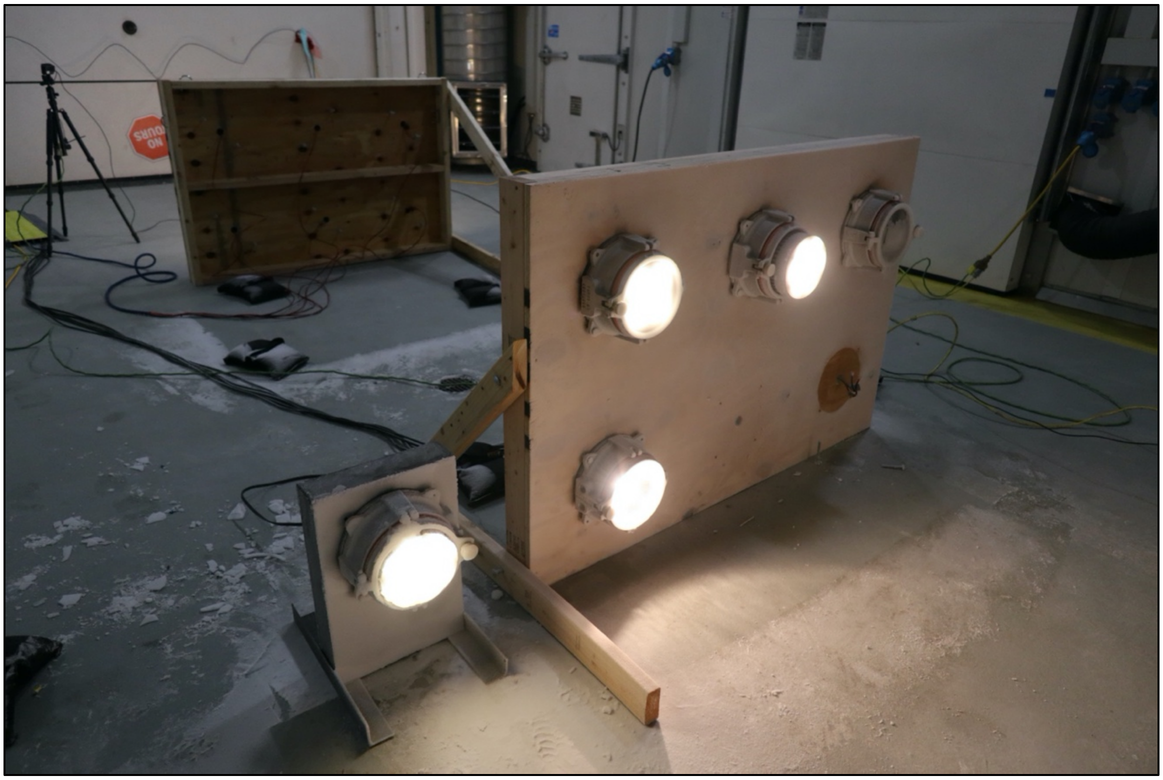


Figure 29. Test frame 2 and metal frame with lamps powered on

Figure 30. LED sample during testing

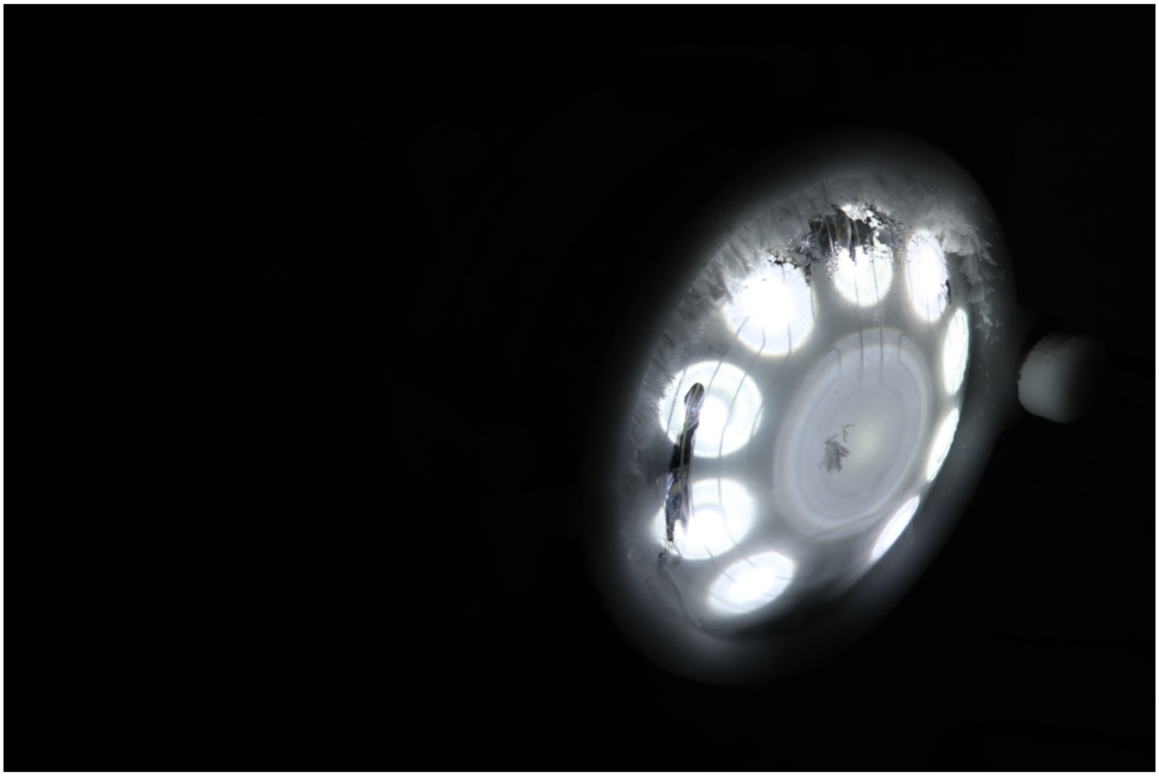


Figure 31. LED sample during testing

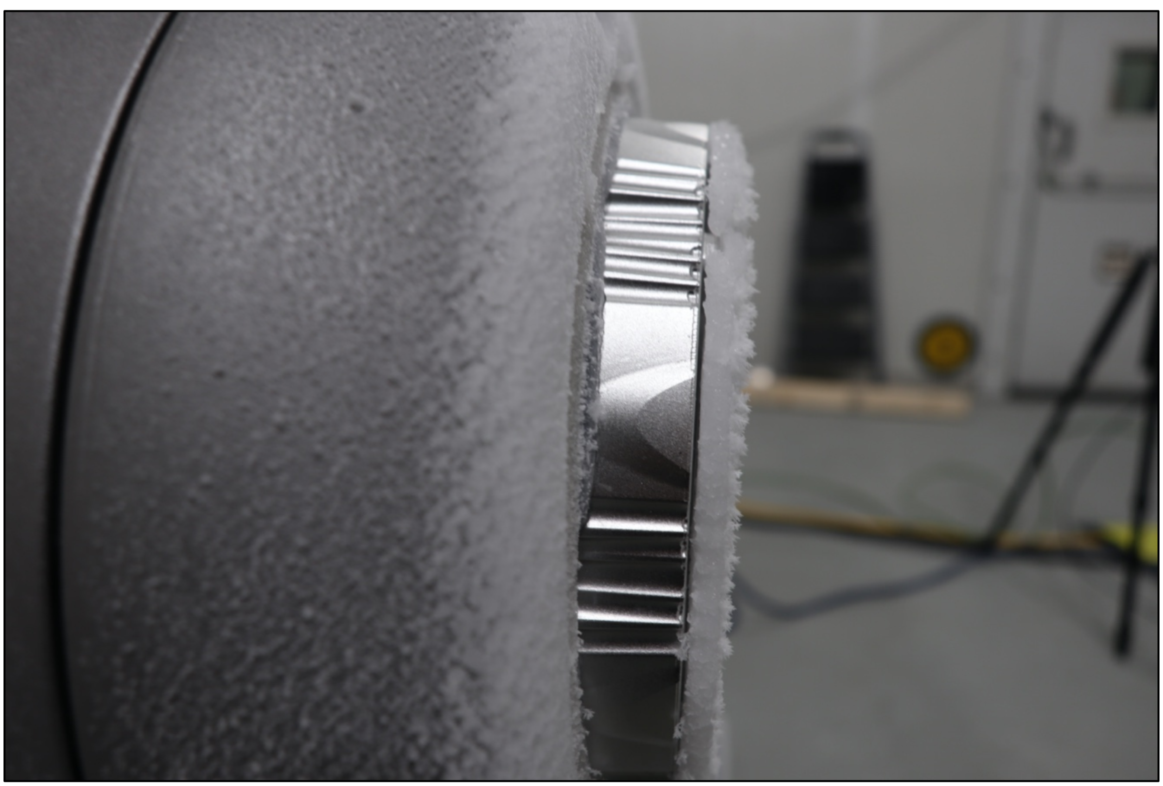


Figure 32. Separation of ice from lens of LED sample

Appendix C.
Snow Accumulation Test – Selected Photographs

Figure 33. Halogen sample after Trial 1

Figure 34. LED sample after Trial 1

Figure 35. LED sample after Trial 1

Figure 36. LED sample after Trial 1

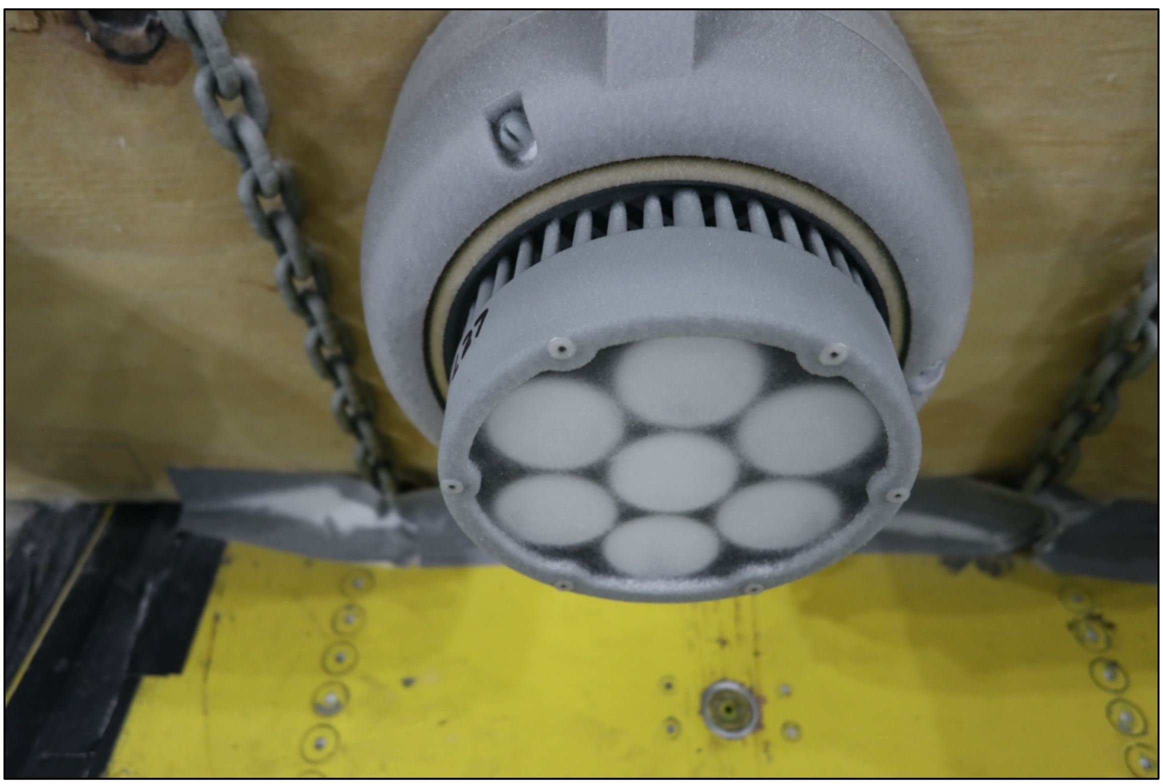


Figure 37. LED sample after Trial 1

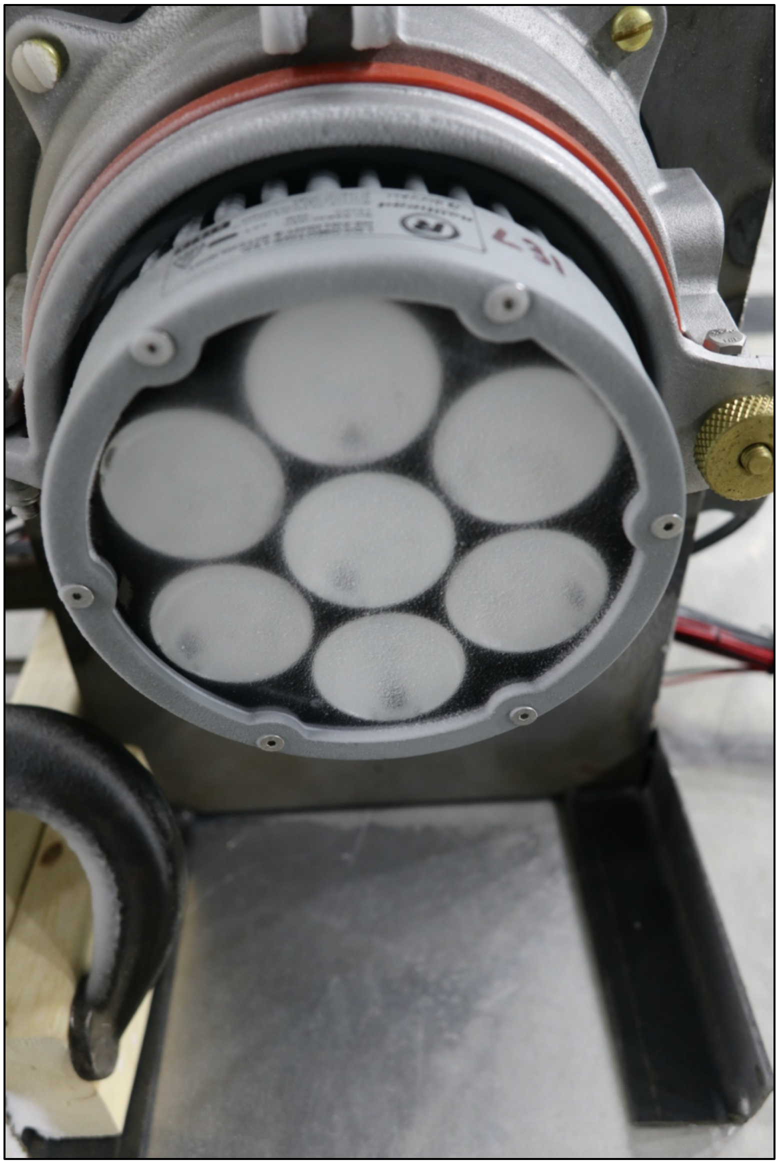


Figure 38. LED sample after Trial 1

Figure 39. Measurement of ice accumulation on LED sample after Trial 1

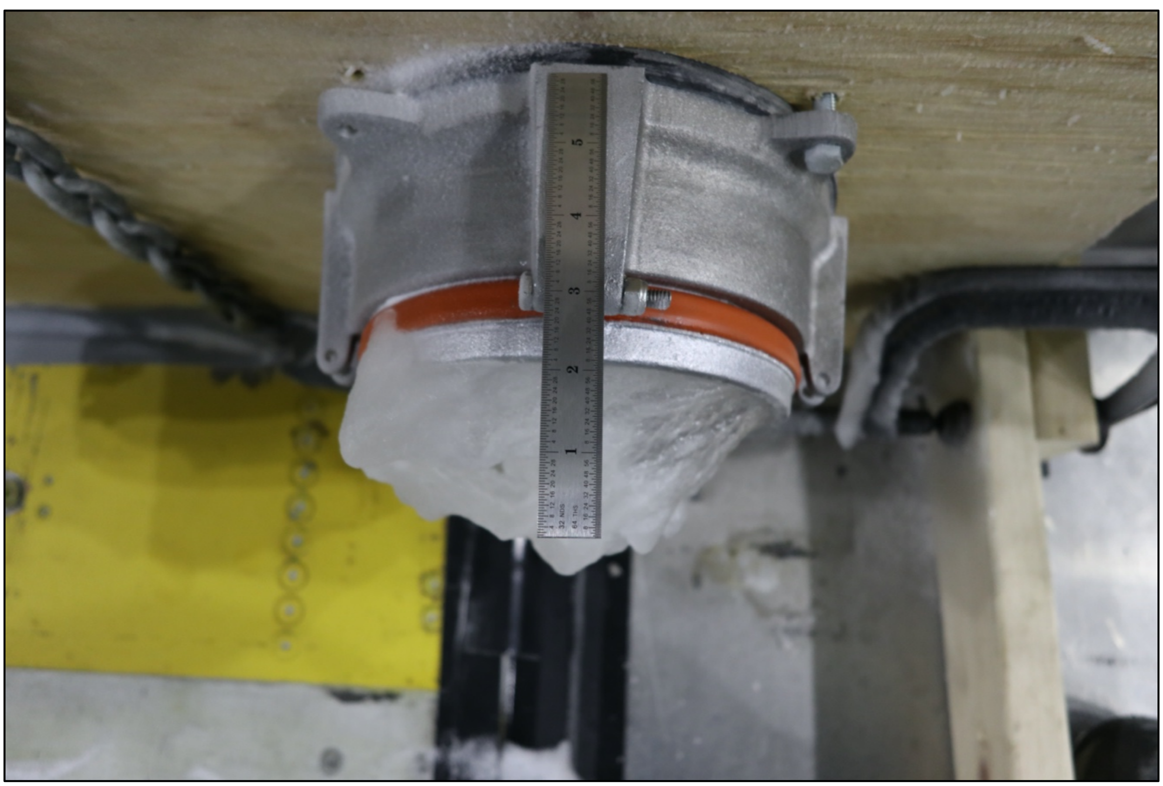


Figure 40. Measurement of ice accumulation on halogen sample after Trial 1

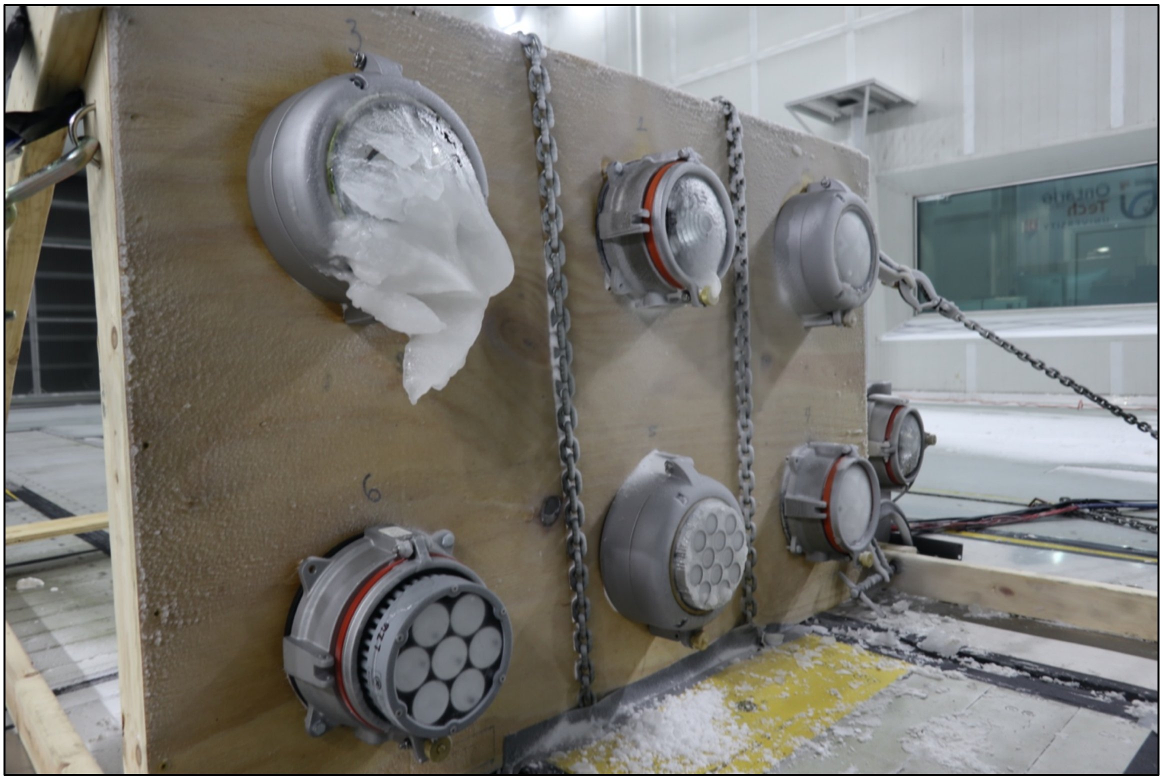


Figure 41. Light fixtures after Trial 2

Figure 42. LED sample after Trial 2

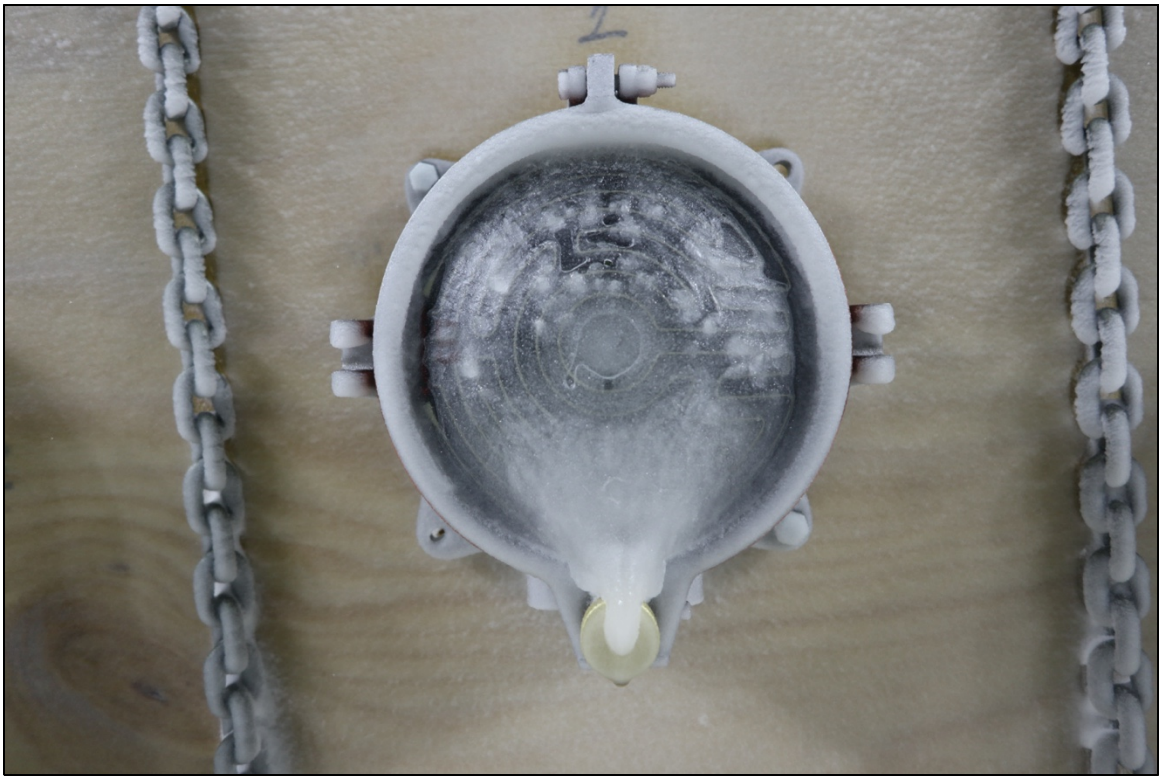


Figure 43. LED sample after Trial 2

Figure 44. Halogen sample after Trial 2

Figure 45. LED sample after Trial 2

Figure 46. LED sample after Trial 2 (non-powered sample)

Figure 47. LED sample on metal testing frame after Trial 2

Figure 48. Documentation of ice on LED sample after Trial 2

Figure 49. Documentation of ice on LED sample after Trial 2

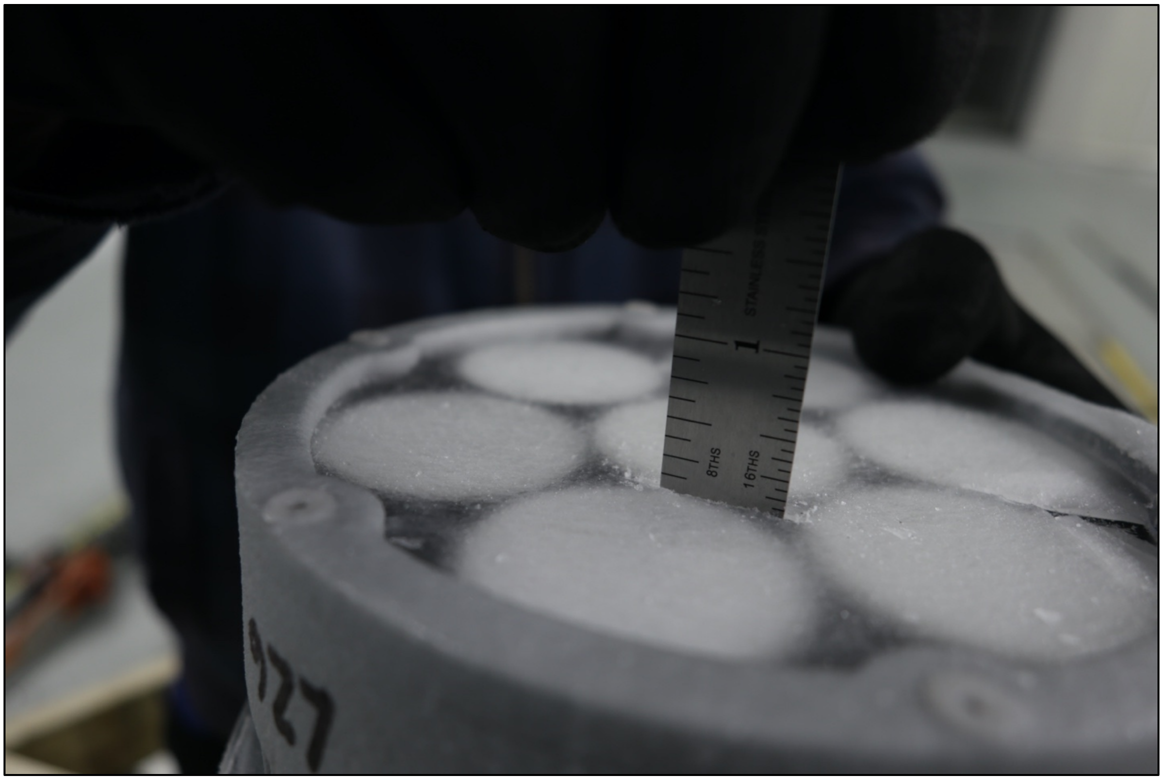


Figure 50. Measurement of ice thickness on LED sample after Trial 3

Appendix D.
General Documentation – Selected Photographs

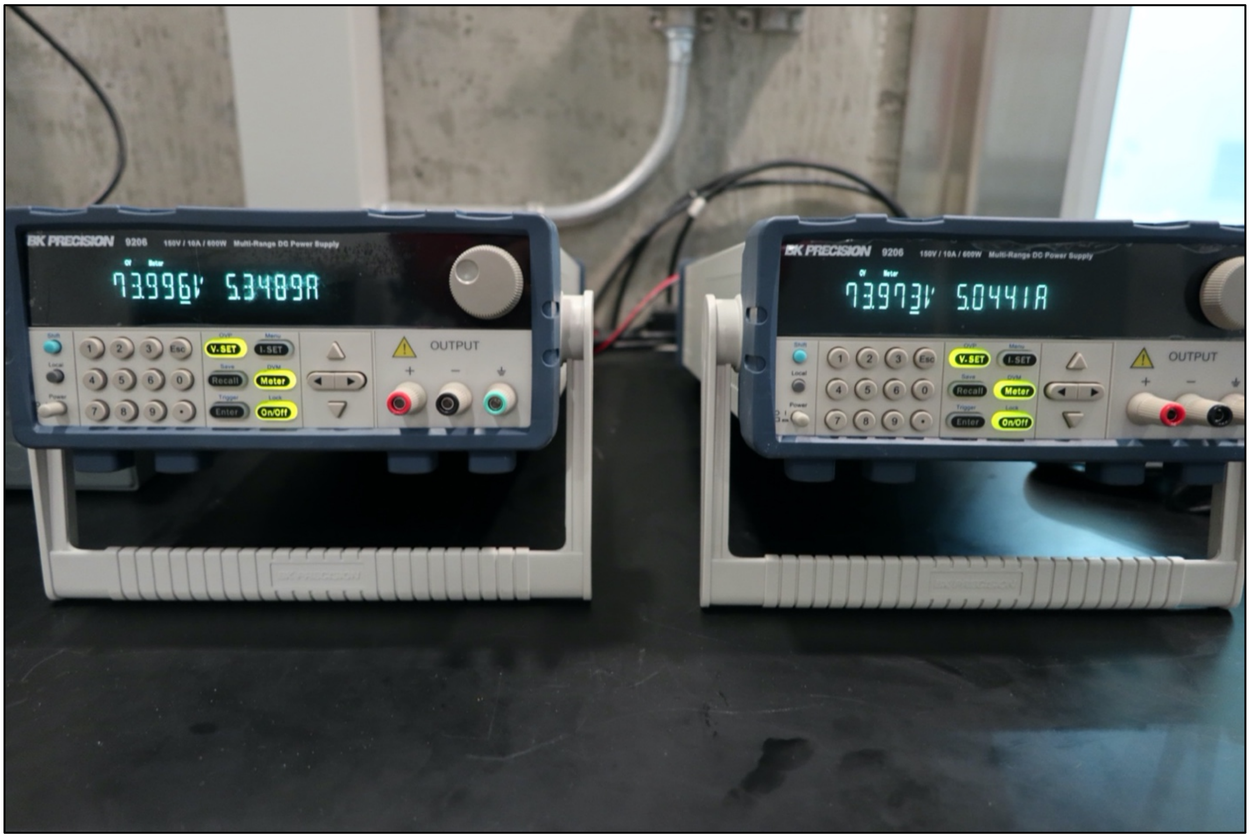


Figure 51. Power supplies used during Snow Accumulation Test

Figure 52. Early stages of the water spraying process

Figure 53. LED sample in the early stages of building the 1/4 inch layer of ice

Figure 54. Halogen sample in the early stages of building the 1/4 inch layer of ice

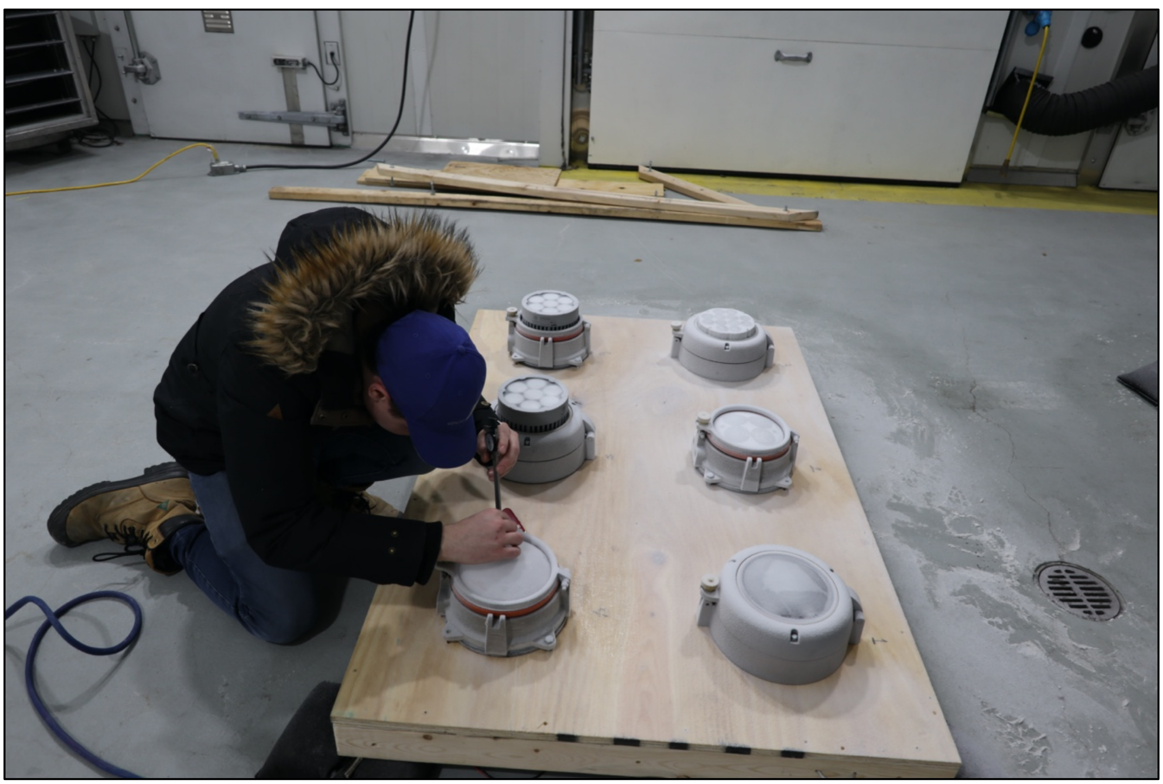


Figure 55. Experimenter measuring the ice layer thickness using a depth gauge

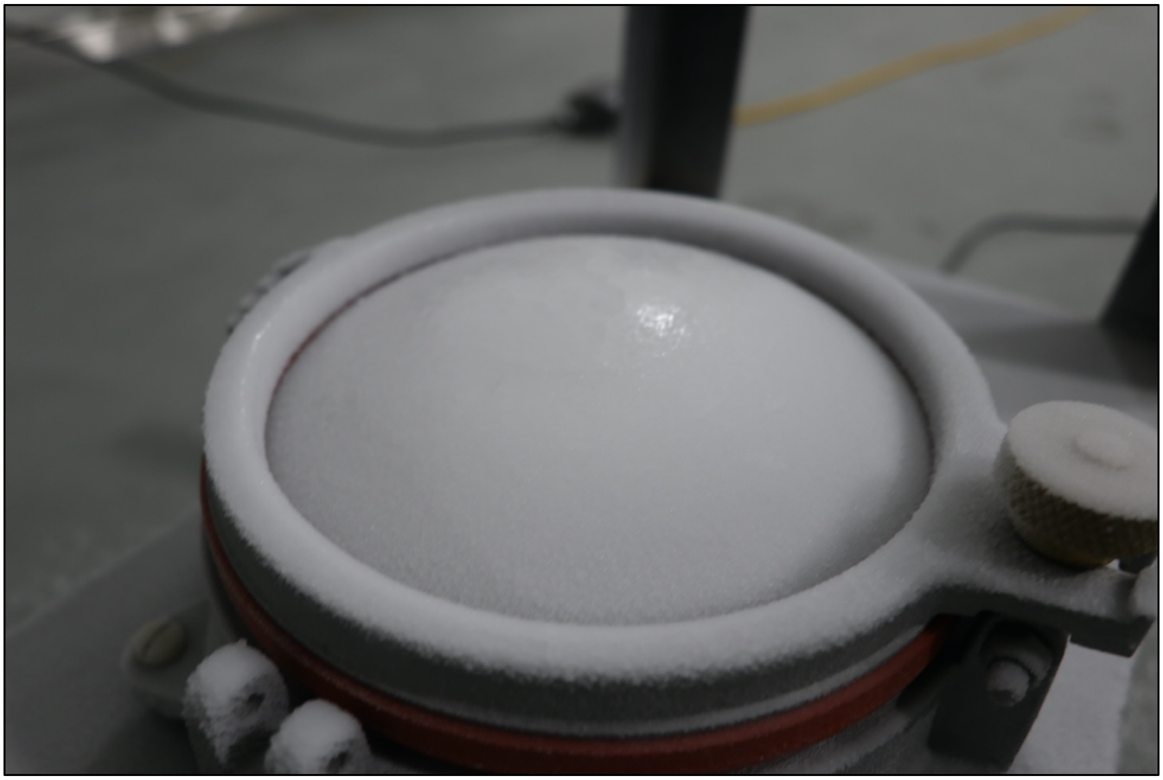


Figure 56. Halogen sample in the late stages of building the 1/4 inch layer of ice

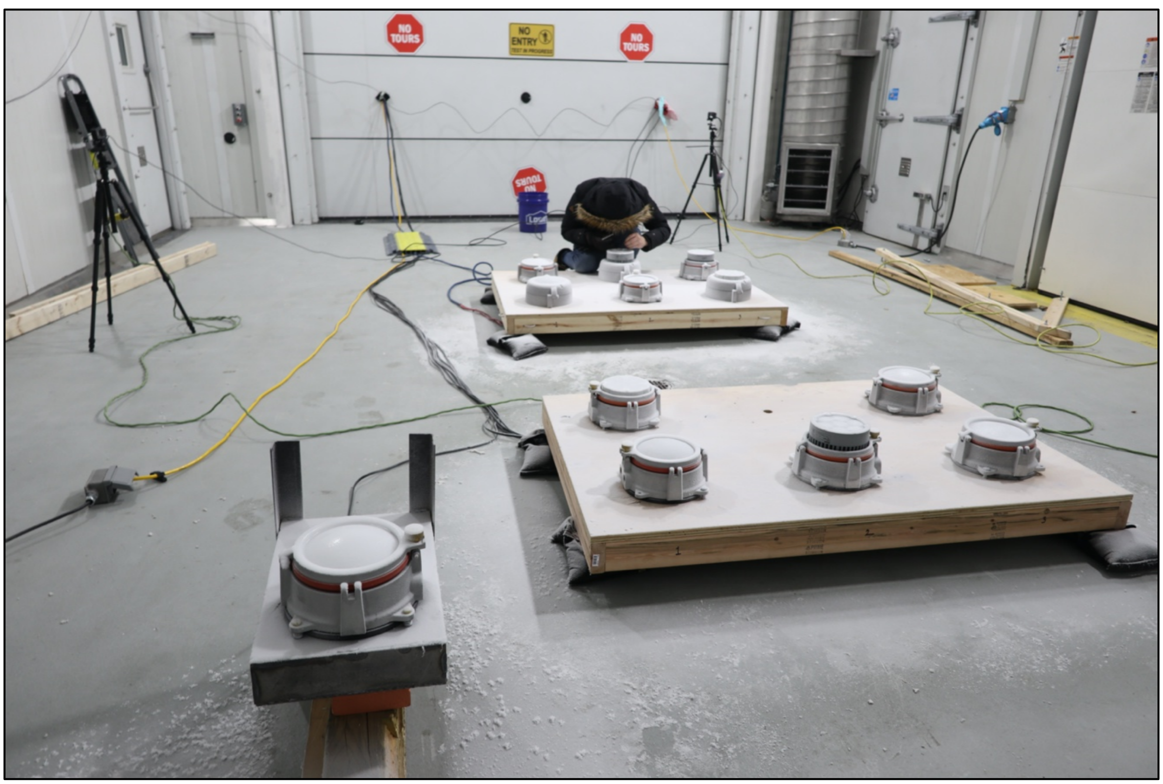


Figure 57. Test frames in the late stages of building the 1/4-inch layer of ice

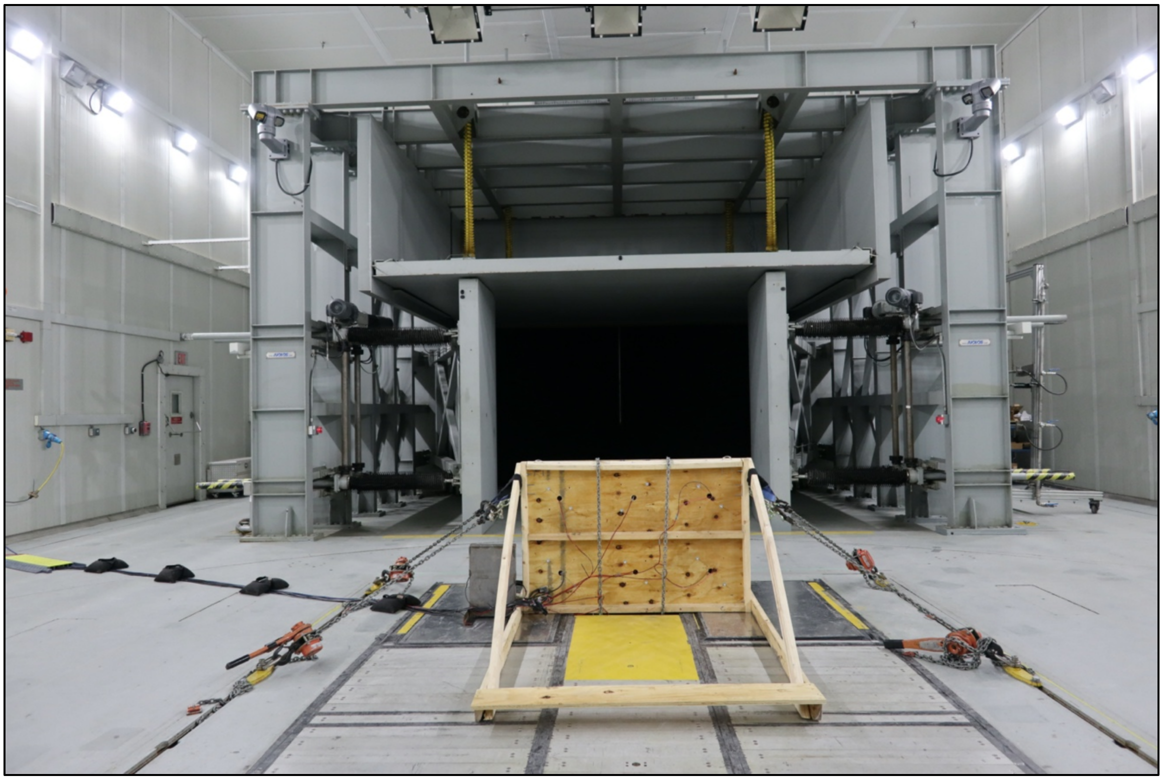


Figure 58. View of the testing area in the CWT

Figure 59. Documentation of snow inside housing

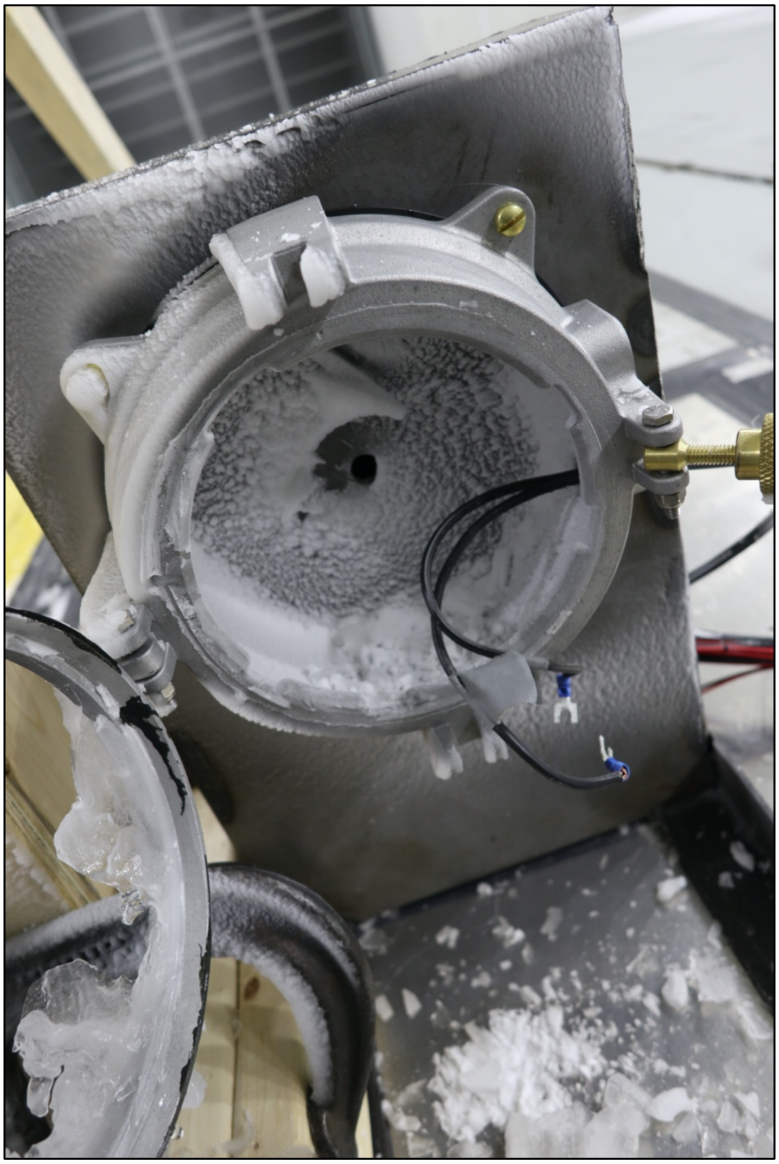
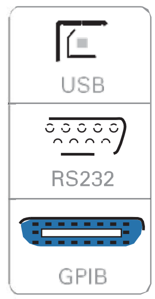


Figure 60. Documentation of snow inside the housing of the metal test frame

Appendix E.
Power Supply Datasheet

Data Sheet

Multi-Range Programmable DC Power Supplies
9200 Series



The 9200 Series can replace multiple supplies on your bench or in your rack. Unlike conventional supplies with fixed output ratings, the 9200 Series automatically recalculates voltage and current limits for each setting, providing max output power in any Volt/Amp combination within the rated voltage and current limits.

These supplies provide a numerical keypad for direct entry of voltage and current values along with convenient cursors and a rotary knob to quickly make incremental voltage and current changes. For remote control, the standard USB, RS232, and GPIB interfaces supporting SCPI commands can be used to remotely control the power supplies via a PC. Alternatively, users can control the power supply, execute test sequences or log measurements using the provided PC software application. This software also integrates with Data Dashboard for LabVIEW apps enabling iOS, Android, or Windows 8 compatible tablets or smartphones to remotely monitor select measurement indicators.

These features make the 9200 Series suitable for a wide range of applications including production testing, R&D, electronic field service, and education.

Model	9201	9202	9205	9206
Max Voltage	60 V	60 V	60 V	150 V
Max Current	10 A	15 A	25 A	10 A
Max Power	200 W	360 W	600 W	600 W

Features

- Multi-ranging operation
- High programming and readback resolution of 1mV / 0.1 mA
- Store and recall up to 72 instrument settings
- Output timer function
- List mode programming
- Standard USB (USBTMC-compliant), RS232, and GPIB interfaces supporting SCPI commands for remote control
- Remote sense
- Thermostatically controlled fan
- Built-in digital voltmeter (DVM)
- Overvoltage/overpower/overtemperature protection, and key-lock function
- NI certified LabVIEW driver and softpanel for remote control, test sequence generation, and datalogging available
- Compact 19” half-rack form factor allows for side-by-side rack mounting of two units

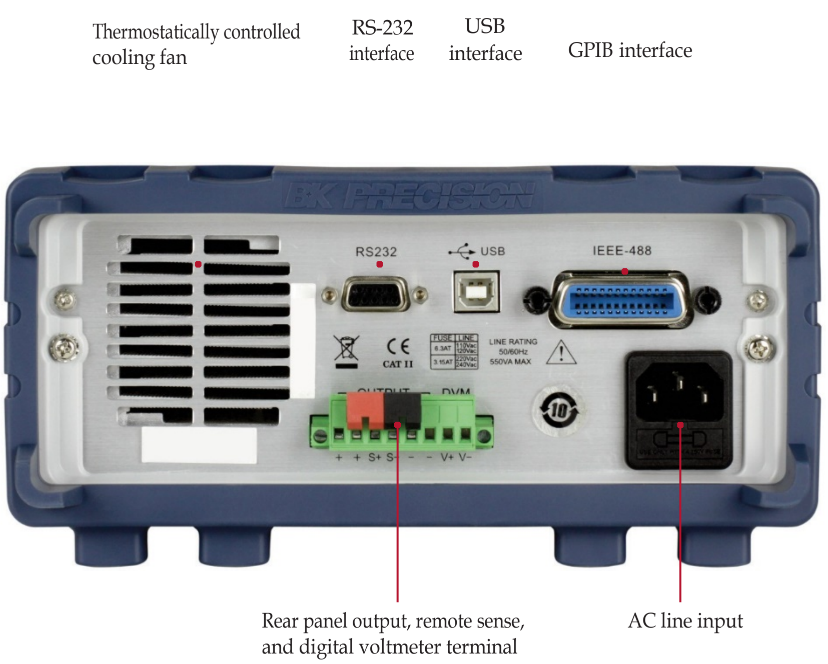
IT-E151 rack mount kit accessory

- ## Front panel

Intuitive user interface

The numeric keys and rotary knob provide a convenient interface for setting output levels quickly and precisely. Use the meter button to quickly toggle between measured and set values. Additionally, the power supplies provide internal memory for storage of up to 72 different instrument settings that can be saved and recalled via the front panel or remote interfaces.

- ## Rear panel



PC connectivity

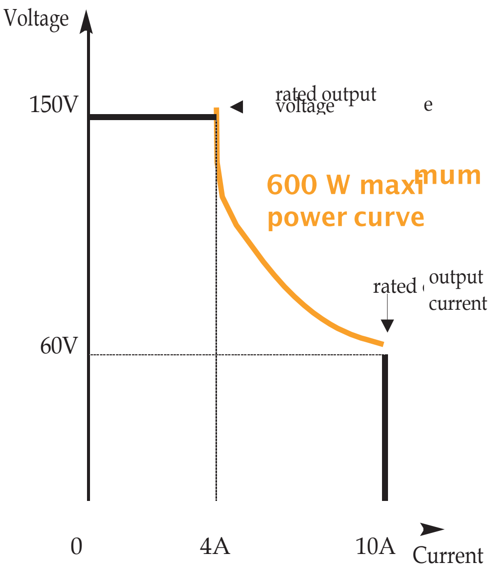
These power supplies offer SCPI IEEE488.2 compatible standard USB (USBTMC-compliant), RS232, and GPIB interfaces to facilitate test system development and integration.

• Flexibility & Performance

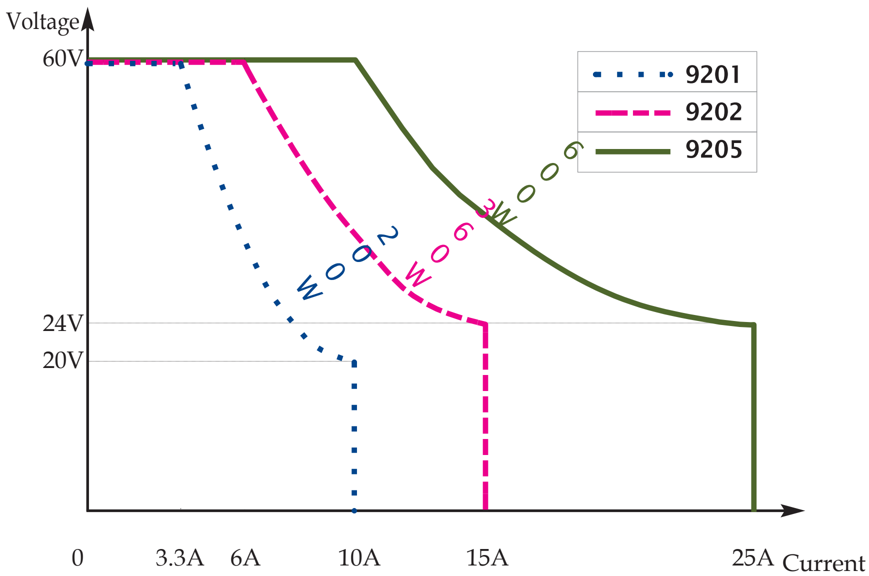
Multi-Range Operation

Traditional power supplies with rectangular output characteristics are only able to deliver maximum output power at one voltage/current point. The multi-ranging 9200 Series provides greater flexibility over traditional power supplies by extending operating areas. For example, the 9206 can operate at 150 V/4 A, 60 V/10 A, or any other point on the maximum power curve. These wide ranges of voltage and current allow users to replace multiple traditional power supplies on a bench or system rack.

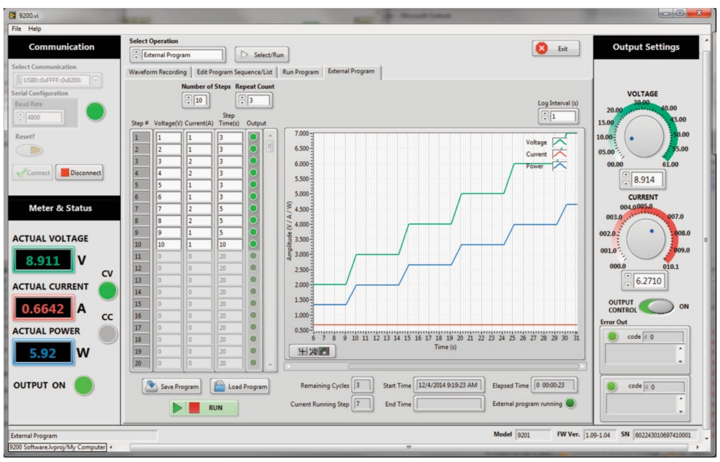
Model 9206 output characteristics



Models 9201 / 9202 / 9205 output characteristics



Application software



PC software is provided for front panel emulation, generating and executing test sequences or logging measurement data without the need to write source code.

- Remote monitoring on iOS, Android, or Windows 8 compatible tablets or smartphones via NI Data Dashboard for LabVIEW apps
- Quickly develop a custom dashboard with indicators, charts, or gauges to monitor your power supply

- Log voltage, current, and power values as well as timestamp, CV/CC mode, and output status
- Save and load list files to and from the power supply's internal memory or a PC

Test sequence execution in list mode

The list mode feature lets users store, recall, and run program sequences in the power supply's internal memory. A total of 10 list files can be saved, each allowing a maximum of 150 configured steps. The test sequence can be programmed from the front panel or remotely via the USB, RS232, or GPIB interfaces. A list file can be set to execute once or repeated multiple cycles. Each step's settings include voltage, current, and duration.

Built-in DVM and output timer

Additional features include a built-in DVM capable of measuring up to 60 V DC and an output timer function. The timer can be adjusted from 0.1 – 99999.9 s and used to set up how long the output is enabled when turned on.

Specifications

Model	9201	9202	9205	9206
Output Rating				
Voltage	0-60 V	0-60 V	0-60 V	0-150 V
Current	0-10 A	0-15 A	0-25 A	0-10 A
Power	200 W	360 W	600 W	600 W
Line Regulation				
Voltage	≤ 0.01%+5 mV	≤ 0.01%+8 mV	≤ 0.01%+15 mV	≤ 0.01%+15 mV
Current	≤ 0.05%+4 mA	≤ 0.05%+6 mA	≤ 0.1%+10 mA	≤ 0.05%+10 mA
Load Regulation				
Voltage	≤ 0.01%+8 mV	≤ 0.01%+8 mV	≤ 0.01%+15 mV	≤ 0.01%+15 mV
Current	≤ 0.05%+6 mA	≤ 0.05%+6 mA	≤ 0.1%+10 mA	≤ 0.05%+10 mA
Ripple and Noise (20 Hz - 20 MHz)				
Voltage	≤ 8 mVpp	≤ 15 mVpp	≤ 20 mVpp	≤ 50 mVpp
Current	≤ 6 mArms	≤ 8 mArms	≤ 15 mArms	≤ 15 mArms
Programming Resolution				
Voltage	1 mV	1 mV	1 mV	1 mV
Current	0.1 mA	0.1 mA	0.1 mA	0.1 mA
Readback Resolution				
Voltage	1 mV	1 mV	1 mV	1 mV
Current	0.1 mA	0.1 mA (<10 A) 1 mA (>10 A)	0.1 mA (<10 A) 1 mA (>10 A)	0.1 mA
Programming Accuracy ± (%output+offset)				
Voltage	≤ 0.03%+5 mV	≤ 0.03%+5 mV	≤ 0.03%+5 mV	≤ 0.03%+20 mV
Current	≤ 0.1%+10 mA	≤ 0.1%+15 mA	≤ 0.1%+25 mA	≤ 0.1%+25 mA
Readback Accuracy ± (%output+offset)				
Voltage	≤ 0.03%+5 mV	≤ 0.03%+5 mV	≤ 0.03%+5 mV	≤ 0.03%+20 mV
Current	≤ 0.1%+10 mA	≤ 0.1%+15 mA	≤ 0.1%+25 mA	≤ 0.1%+25 mA
General				
Remote Sense Compensation	1 V			
DVM Range	0-60 V			
DVM Accuracy	0.02%+10 mV			
DVM Resolution	1 mV			
Standard Interface	USB (USBTMC-compliant), GPIB, RS-232			
AC Input	110/220 VAC (+/- 10 %), 47 Hz - 63 Hz			
Operating Temperature	32 °F to 104 °F (0 °C to 40 °C)			
Storage Temperature	-4 °F to 158 °F (-20 °C to 70 °C)			
Dimensions (W×H×D)	8.45″ x 3.47″ x 13.96″ (214.5 x 88.2 x 354.6 mm)		8.45″ x 3.47″ x 17.52″ (214.5 x 88.2 x 445 mm)	
Weight	16.98 lbs. (7.7 kg)		33.07 lbs. (15 kg)	
				Three-Year Warranty
Standard Accessories	User manual, power cord, & certificate of calibration			
Optional Accessories	IT-E151 rack mount kit			

Appendix F.
ACE Laboratory Technical Specifications Sheet

Automotive Centre of Excellence

Facility Fact Sheet

- **What is ACE?**

The Automotive Centre of Excellence (ACE) is the first testing and research centre of its kind in Canada. It is wholly owned and operated by Ontario Tech University and is located on the north campus in Oshawa, Ontario.

ACE is a truly independent test facility that is commercially available to customers who are seeking to bring their ideas into a proof of concept and ready for market. This is where the next generation of electric and alternative fuel vehicles, green energy technology will be discovered, tested and validated.

ACE is a multi-purpose centre with an area of approximately 16,300 square metres. It is divided into two distinct sections: a core research facility and an integrated research and training facility. The total cost of the facility is approximately $100 million.

ACE was developed in partnership with Ontario Tech, General Motors of Canada, the Government of Ontario, the Government of Canada and the Partners for the Advancement of Collaborative Engineering Education (PACE).

- **What is the core research facility?**

The core research facility is a heavy lab area with five distinctive test chambers:

- **Climatic Wind Tunnel** – ACE has one of the largest and most sophisticated climatic wind tunnels in the world. In this test chamber, wind speeds can exceed 250 kilometres per hour, temperatures range from -40 to +60°C and relative humidity ranges from 5 to 95 per cent. The climatic wind tunnel has a unique variable nozzle that can optimize the airflow from 7 to 13 metres squared allowing for an unprecedented range of vehicle and other test property sizes. Coupled with this feature is a large chassis dynamometer that is integrated into an 11.5-metre turntable. Now, for the first time anywhere, vehicles and test properties can be turned into the airstream under full operating conditions to facilitate vehicle performance testing in a crosswind development. The large open chamber has a readily reconfigurable solar array that will replicate the effects of the sun and is hydrogen-capable, allowing for alternative fuels and fuel cell development.

- **Climate Chambers –** ACE has a large and a small climate chamber that provide exacting conditions of both temperature and humidity. The large climate chamber is a high feature chamber that includes an input dynamometer coupled with a solar array. Temperatures range from -40°C to +60°C and relative humidity from 5 to 95 per cent.

- **Climatic Four-Poster Shaker** – ACE has a drive-on four-poster shaker within a climatic chamber. This vertical axis shaker can provide the motion for simulated drive surfaces to validate suspension and body durability for applications like squeak and rattle. In addition, the four-poster is capable of providing highly accelerated motion further enhancing its capabilities to support advanced structural durability and life cycle testing. Temperatures range from -40°C to +60°C and relative humidity from 5 to 95 per cent.

- **Multi-Axis Shaker Table (MAST)** – ACE has a multi-axis shaker table or MAST in a hemi-anechoic chamber. The six axis inverted hexapod design allows for products to be tested for structural durability and the detection of noise and vibration in three dimensions.

- **Secure Preparation Garages** – ACE has three secure preparation garages, with exhaust extraction system, tool chest, work bench and electric power.

- **What is the Integrated Research and Training Facility?**

The integrated research and training facility spans five floors with space dedicated for research, education and training. It has offices, laboratories, conference rooms and common work areas that are available to rent. This facility will foster an environment for collaboration and interaction between industry, researchers and students.

- **What are the potential markets?**

In addition to conventional automotive applications, ACE is suitable for testing alternative fuel, hybrid and electric vehicles. It is large enough to accommodate trucks, tandem drive systems, full coach buses, light rail transit, aerospace, military and agricultural applications, wind turbines and solar panels. Furthermore, ACE could be used to train military personnel, rescue crews or competitive athletes, to carry out performance testing of outdoor survival gear. It has the potential to assist the movie industry or test products that are subject to severe wind, humidity, snow, icing or desert heat.

- **Booking ACE**

ACE is available to rent by those with a need for its unique capabilities, including: manufacturers of all descriptions, start-up companies and researchers in Canada and from around the world. Clients can rent the entire facility or specific chambers at an hourly rate that is globally competitive.

For more detailed information or to take a tour of ACE, please visit our website at: www.ontariotechu.ca/ace.

ACE WIRELESS ENVIRONMENT - Key Features

ACE has invested in additional capabilities to help developers of autonomous, connected car and wireless automotive systems.

GNSS (Global Navigation Satellite Systems) simulation. Allow generation of fixed and moving profile of coordinates based on GPS, Galileo, BeiDou and/or GLONASS networks. Power levels are controllable and any coordinates are possible. Useful for checking GNSS module sensitivity vs. climate or for doing other tests when GNSS system like GPS is required to enhance the simulation.

Summer (June 2019)

V2X transmission standards, specifically DSRC, ITS-G5 and WAVE power analysis vs. climate using the 802.11p standard. Set a reference power level with your module, change the environment and see how your transmission power has been affected.

Possible in the future (2020)

Enhancement to include C-VSX based on 3Gpp release 16 to measure module transmission power analysis vs. climate on this new standard.

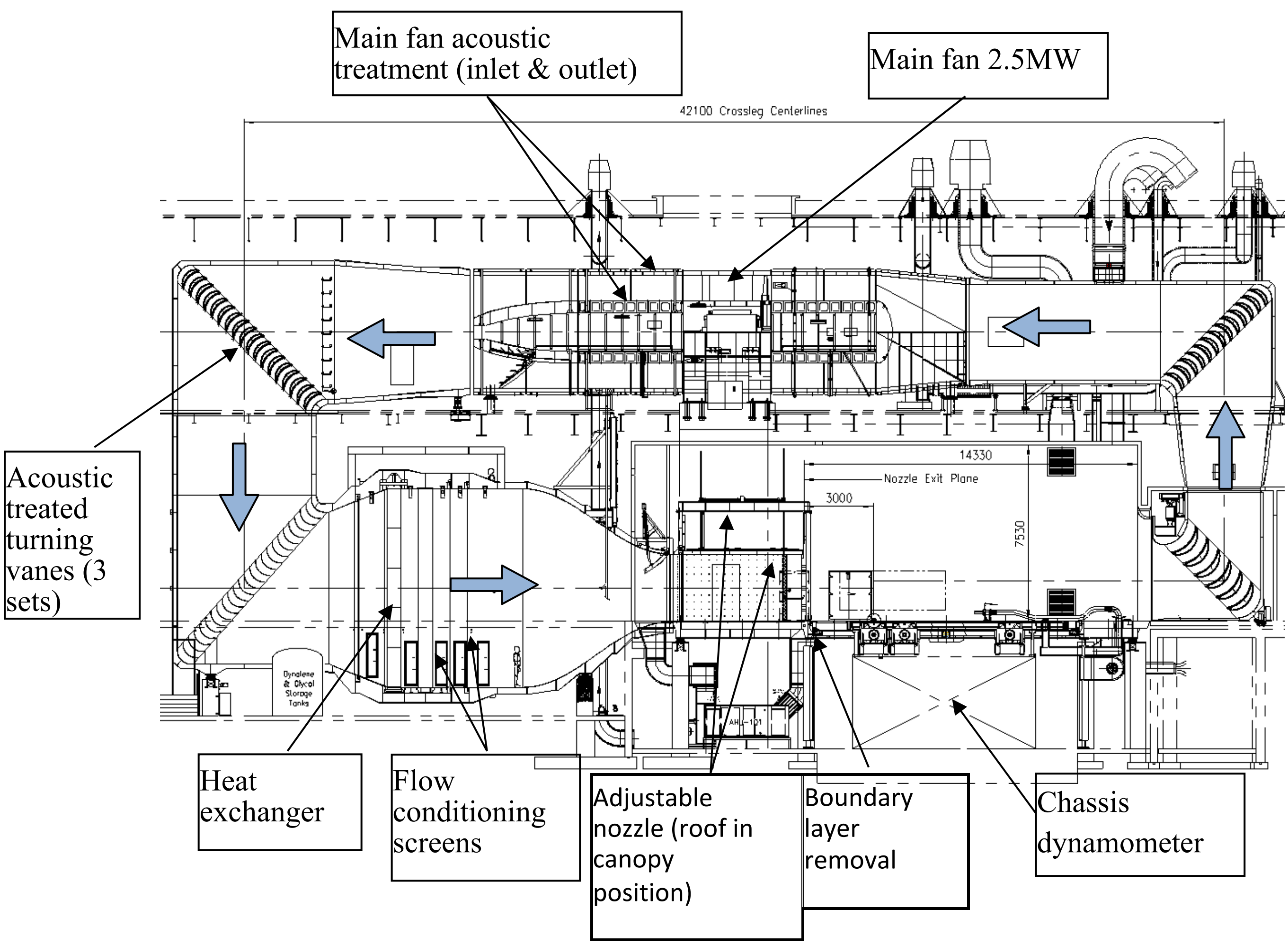
High performance electronic troubleshooting equipment provided by Keysight (formerly Agilent) Technologies. Exceptional array of general-purpose equipment covering DC to 6.5Ghz and thermal imaging allow visitors to repair, or tweak their modules without having to fly home or import/bring their own test equipment.

- 4.5 digit True RMS Handheld DMM
- Digital multimeter, 6 1/2 digit, including voltage, current 4 wire resistance, capacitance and digitizing over LAN or USB
- DC power supply, triple-output, 6 V, 10 A and 2 x 25 V, 2 A, 160 W: LAN, USB controllable
- DC Power Supply 60V, 12.5A, 750W; GPIB, LAN, USB, LXI compliant
- Data Acquisition Switch Unit with LAN and USB, and 20 channel Relay mux based on DAQ970A
- Multifunction DIO and analog output for data acquisition system
- Oscilloscope, 4-channel, 500 MHz with built in Function Generator, CAN/LIN/I2C, SPI, and more decodes. USB controllable.
- 6.5 GHz FieldFox RF Analyzer including Vector Network analysis, Spectrum analyzer with preamplifier and interference analysis, CW signal generation TDR cable measurements and GPS receiver
- Perpetual transportable license BenchVue CCC, Control and Automation
- TrueIR Thermal Imager, -20 to 350 degree Celsius
- BenchVue Instrument control and automation with easy export of data and saving bench states.

CLIMATIC WIND TUNNEL *- Key Features*

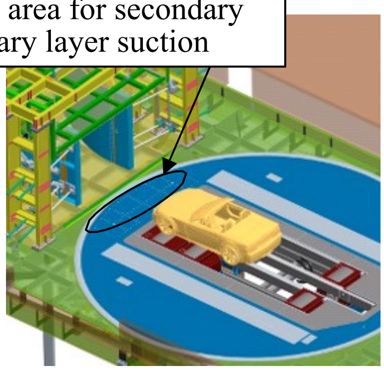
- Adjustable nozzle 7- 13m^2 and long test section to accommodate a wide range of vehicle sizes and type, from small cars to Class 8 trucks and buses, with wind speeds in excess of 240kph
- Temperature from -40^{o}C to +60^{o}C and humidity from 5% to 95% RH
- Exceptional flow quality for advanced aerodynamic simulation in thermodynamic testing
- Low background noise level (64dBA at 50kph) for the detection of vehicle drive-away anomalies such as misfires, transmission hesitation, etc.
- Unique independently-power rolls chassis dynamometer in a turntable to enable cross-wind testing
- Solar simulation system up to 1200W/m^2 intensity with sunrise-sunset simulation capabilities
- Blowing rain, falling and blowing snow simulation
- Complete suite of ancillary systems for customer vehicle operation, including hydrogen and electric vehicle compatibility

Wind Tunnel Circuit

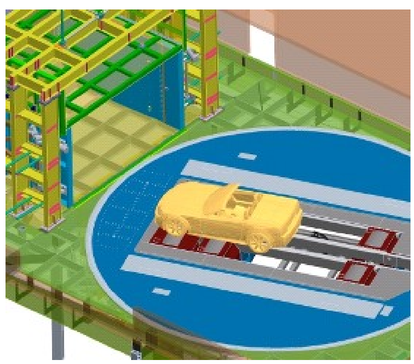


Test Section Features

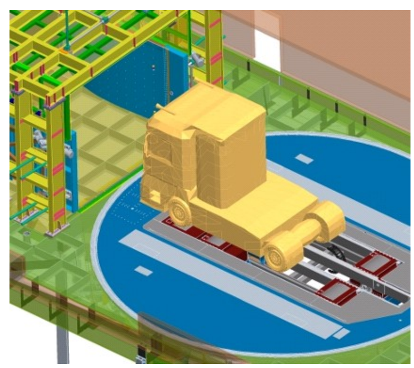
Overall dimensions	L20.1m x W13.5m x H7.5m
Useable length	• 14.3m for cars & trucks • 19.1m for trucks & buses
Vehicle entry clearance	W3.93m x H4.49m (Corner No.1 turning vane set open)
Adjustable nozzle	• 7.0 – 13.0m^2: H2.9m x W2.4 – 4.5m
Canopy for buses	22m^2: H4.4m x W5m (used with 13.0m^2 nozzle)
Turntable diameter	11.7m
Boundary layer removal	• W5.25m main suction system • Provision for secondary suction
Vehicle exhaust extraction system	• Dual or single exhaust pipes • Open or closed mode with back pressure regulation • Maximum flow rate: 0.62kg/sec (8.5 liter, 400 HP engine) • Maximum inlet exhaust temperature: 650^{o}C
In-chamber fueling	• Station for Regular, RVP and Diesel • Plumbed in for hydrogen
In-chamber power	Outlets for plug-in vehicles



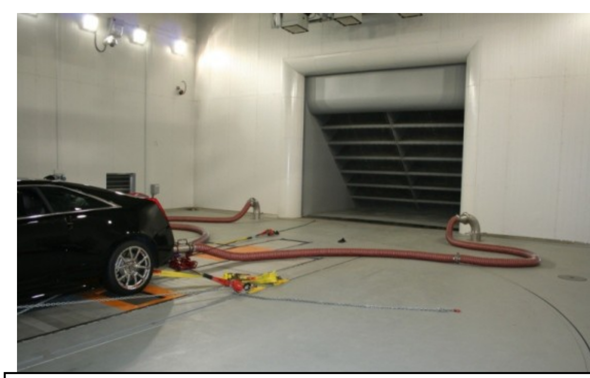
7.0m^2 nozzle, 0^o yaw



13.0m^2 nozzle, 30^o yaw



13.0m^2 nozzle, 22m^2 canopy; 0^o yaw

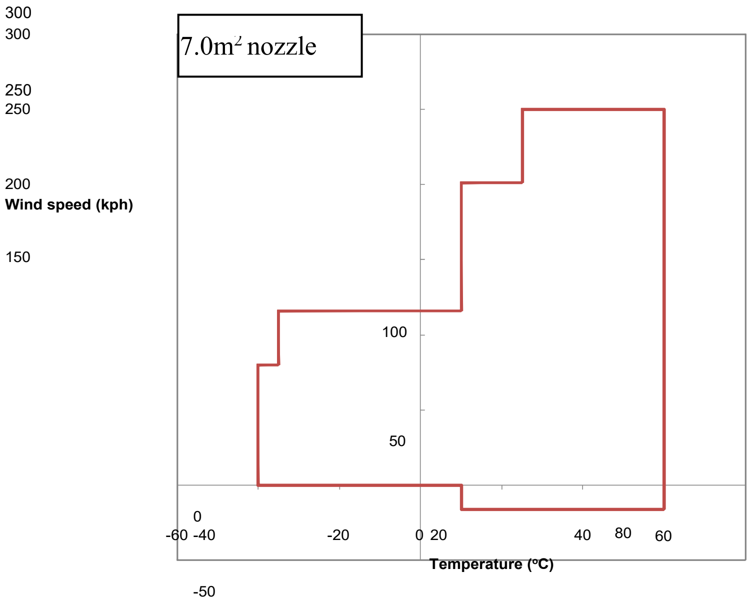


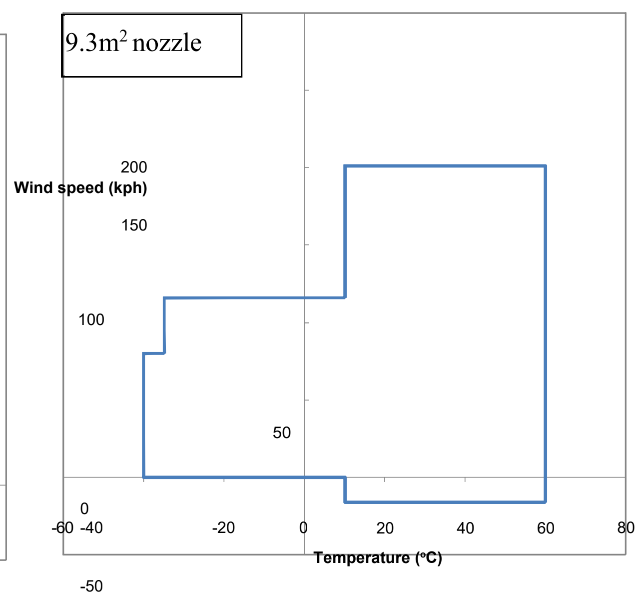
Dual closed-pipe vehicle exhaust extraction system

In-chamber refueling station

- *Wind Speed and Thermal Performance*

***Full thermal control wind speed**: 7.0-9.3m² nozzle settings*

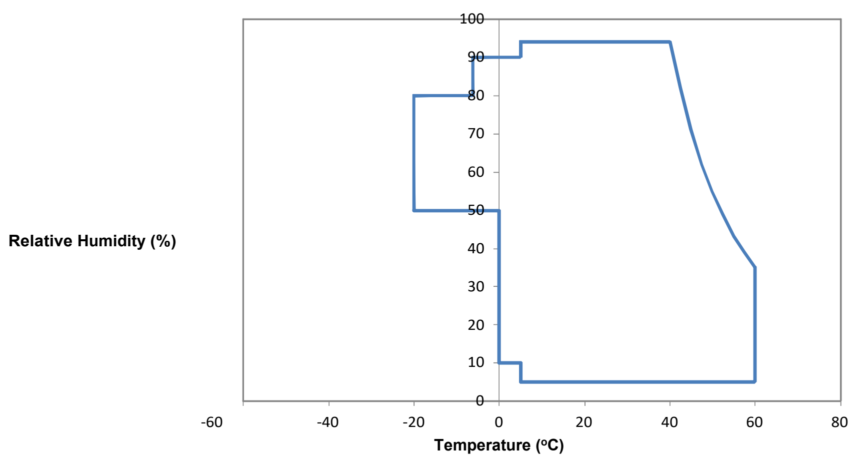




***Increased maximum wind speed**: ambient conditions*

Nozzle (m^2)	Wind speed (kph)	Temperature (ºC)
7.0	280	25
9.3	250	25
13.0	225	25

Humidity – temperature performance



- *Thermal Performance and Flow Quality Specifications*

Cooling system

- R507 primary loop with Dynalene HC-50 secondary loop
- Total heat capacity: 500kW at -40°C , 2100kW at ambient

Thermal performance

Parameter	Set Point Change	Rate	Test Condition
Temperature	<12°C	0.8°C/min	70-105kph; 32°C to 50°C
	<6°C	0.6°C/min	<115kph
	>6°C	0.08°C/min	<115kph
Humidity	20% RH	1.0% RH/min	38°C dry bulb

Flow quality

Parameter	Uniformity (σ)	Stability
Wind speed	1% of set point	±0.5kph
Flow angularity	0.5°	
Temperature	0.3°C	±0.2°C at velocity > 48kph
Humidity	0.5°C (dew point)	±0.5°C (dew point)

Boundary layer displacement thickness

δ* less than 5mm at 0.9m ahead of the front chassis dynamometer roll set at 90kph, 25°C air temperature.

Background noise level: 9.3m² nozzle

Wind speed (kph)	Out-of-flow SPL (dBA)
50	64
100	81
140	90
250	107

- *Chassis Dynamometer Specifications*

Manufacturer & Model	Burke E. Porter (custom design)
Vehicle types	Passenger car, light and medium duty trucks, buses
Axle configurations	FWD, RWD, 4WD, AWD (4 independent rolls)
Roll width	812mm (4 identical)
Roll diameter	1219mm (4 identical)
Roll surface	Tungsten carbide, aggressive finish (0.8µ)
Clear space between rolls	1067mm (identical front and rear)
Wheelbase range	1600 to 5842mm
Location of front fixed axle from nozzle exit plane (0° yaw)	3000mm
Location of rear fixed axle from nozzle exit plane (180° yaw)	9200mm
Normal maximum yaw angle range	±30°
Floor features	• Automatic floor track and side roll cover system • Moveable central inspection port with infrared camera
Total inertial simulation range	907 to 9072kg
Maximum axle load	5000kg
Maximum vehicle weight	9072kg
Maximum speed	250kph
Motor type	AC (Vector Drive Duty)
Nominal maxim power	187kW per roll, motoring and absorbing; 92 to 250kph
Base speed	92kph
Continuous tractive force rating	7301N per roll ; 0 to 92kph
Tractive force overload	150% for 60 seconds; 0 to 92kph
Features	Robot driver; customer specified drive cycles
Configuration	Elevator and air bearings permit removal from test section

Side floor track covers

Central floor track cover

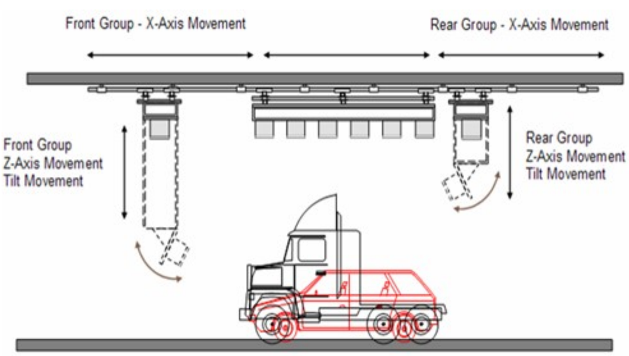
Elevator

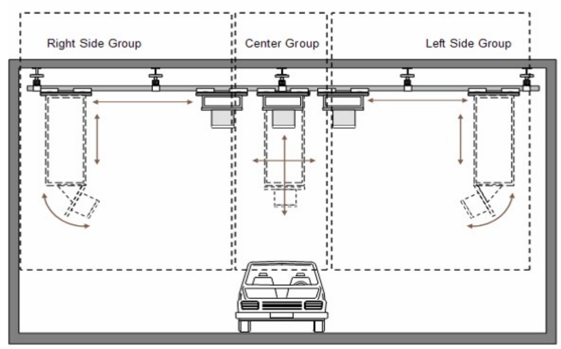
Air bearing

Solar Simulation System Specifications

- Full diurnal function with azimuth and altitude
- Full spectrum capability with vertical and bi-axial movement

Manufacturer	KHS Steuernagel
Target size	• L6.5m x W2.5m • 1.5m above test section floor
Intensity range	600-1200W/m^2
Intensity incidence	0 to 52.5°
Spectrum	ASTM Std E-892
Intensity quality	• Uniformity ±10% • Stability ±2%
Lamps	• Metal halide • 21 total





Solar array showing front illumination (9.3m^2 nozzle)

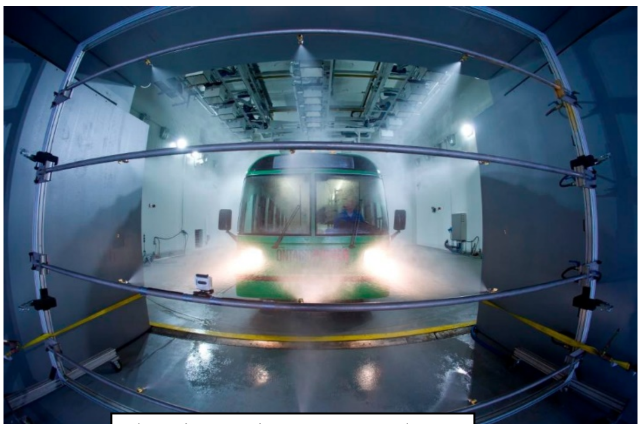
Solar array arranged for a bus (13m^2 nozzle and 22m^2 canopy)

- *Rain and Snow System Specifications*

Rain Simulation System

Frontal rain simulation system located at the nozzle exit provides:

- Up to 12 nozzles of various sizes as needed to provide adequate coverage of a given vehicle
- Designed for 150kph at 20°C but will operate as low as -5°C to perform freezing rain tests.



Blowing rain test on a bus

Measuring freezing rain on a bus

Snow Simulation Systems

There are two configurations of snow simulation possible: frontal (blizzard) and overhead. In both cases, snow guns are used to create the snow.

Blizzard: 30º yaw into the

- *Ancillary Equipment*

Vehicle starting power	200amp 12vDC and 24vDC
Pressure radiator fill	System capable of charging from a pressurized vessel
Gas tank and differential cooling	Cooling water system to provide cooling during high load tests
Refrigerant charging system	• Two charging systems, one for R134A or equivalent, the other for alternative refrigerants • Capability to pull a vacuum once refrigerant has been reclaimed.

Secure preparation

LARGE CLIMATE CHAMBER - Key Features

- Exceptionally long test section to permit articulated buses
- Temperature from -40°C to +60°C and humidity from 5% to 95% RH
- Chassis dynamometer
- Solar simulation system up to 1200W/m^2 intensity
- Inter-chamber door to Small Climate Chamber to permit insertion of a test bench to effect a 'three chamber' mode
- Complete suite of ancillary systems for customer vehicle operation, including hydrogen and electric vehicle compatibility

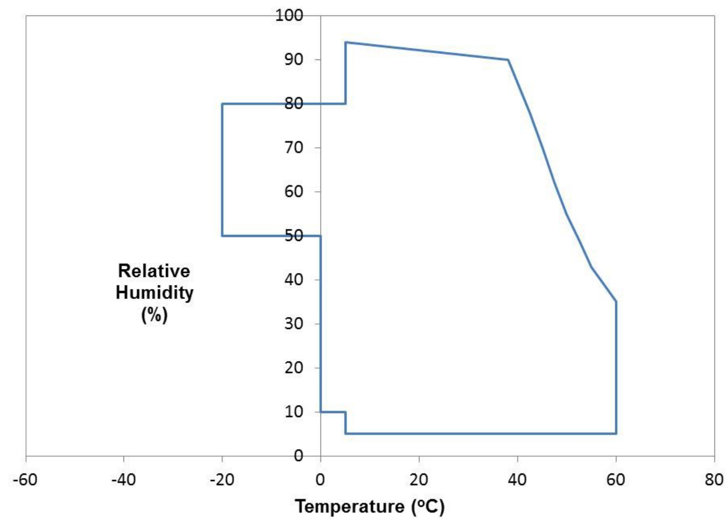
- ### *Test Section Features*

Overall dimensions	L20.8m x W6.0m x H5.55m
Vehicle entry clearance	• W3.93m x H4.49m to outside • W4.26m x H4.49m to transfer area
Inter-chamber door clearance	W2.01m x H2.01m
Primary exhaust extraction system	• Dual mode: open pipe or closed pipe with back pressure regulation • Maximum flow rate: 0.62kg/sec (8.5 liter, 400 HP engine) • Maximum inlet exhaust temperature: 650°C
Secondary vehicle exhaust extraction system	• Garage type open pipe (2 pipes)
In-chamber power	• Outlets for plug-in vehicles

Door to outside

Inter-chamber

Thermal Performance Specifications



Other performance:

- Maximum cooling rate: +60ºC to -40ºC in 6 hours
- Temperature uniformity: σ = 0.33 °C (tested at 20 °C)

- ## *Chassis Dynamometer Specifications*

Manufacturer & Model	Mustang Engineering Co (MD-AWD-500-SE)
Vehicle types	Passenger car, light duty trucks
Axle configurations	FWD, RWD, 4WD, AWD
Roll width	940mm (7 identical per side: 5 front, 2 rear)
Clear space between rolls	610mm (identical front and rear)
Wheelbase range	2134 to 3556mm
Mechanical Inertia	• 636kg Front (Motorcycle mode) • 888kg Front • 983kg Rear
Total inertial simulation range	655 (motorcycle) to 907 (single axle) to 5448kg (dual axle)
Maximum axle load	2727kg
Maximum vehicle weight	5448kg
Maximum speed	• 280kph FWD • 240kph AWD
Motor type	• Eddy current, power absorbing only
Nominal maximum power	• 447kW Front roll set • 894kW Total
Continuous tractive force rating	• 6227N Front roll set • 12455N Total

Solar Simulation System Specifications

Manufacturer	KHS Steuernagel
Target size	• L5.6m x W2.5m (fixed) • 1.5m above test section floor
Intensity range	600-1200W/m^2
Spectrum	ASTM Std E-892
Intensity quality	• Uniformity ±10% • Stability ±2%
Lamps	• Metal halide • 18 total

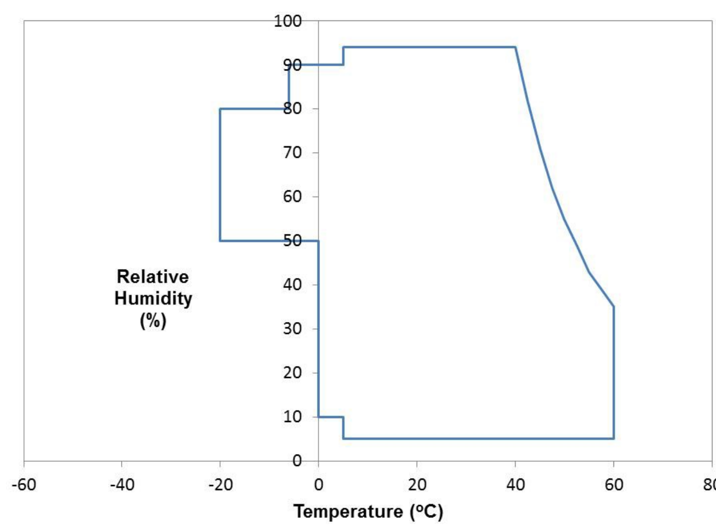
***SMALL CLIMATE CHAMBER** – Key Features*

- Large enough to accommodate two cars
- Temperature from -40°C to +60°C and humidity from 5% to 95% RH
- Inter-chamber door to Large Climate Chamber to permit insertion of a test bench to effect a 'three chamber' mode
- Directly linked to climatic wind tunnel via dry transfer area
- Complete suite of ancillary systems for customer vehicle operation, including hydrogen and electric vehicle compatibility

- ### *Test Section Features*

Overall dimensions	L9.0m x W6.0m x H5.5m
Vehicle entry clearance	• W3.68m x H4.49m to outside • W4.26m x H4.49m to transfer area
Inter-chamber door clearance	W2.01m x H2.01m
Passive exhaust extraction	Garage type
In-chamber power	Outlets for plug-in vehicles

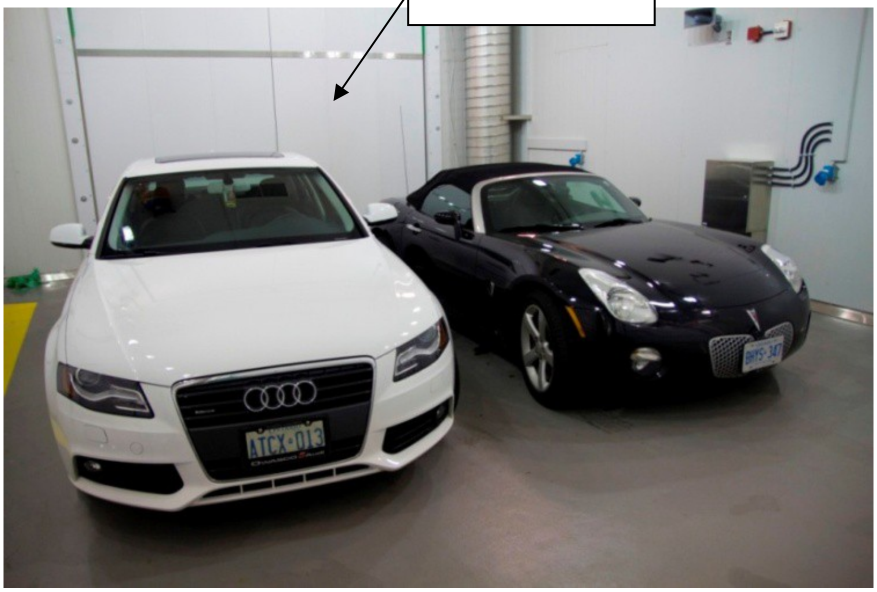
Thermal Performance Specifications



Other performance:

- Maximum cooling rate: +60°C to -40°C in 6 hours
- Temperature uniformity: σ = 0.17 °C (tested at 20 °C)

Door to outside



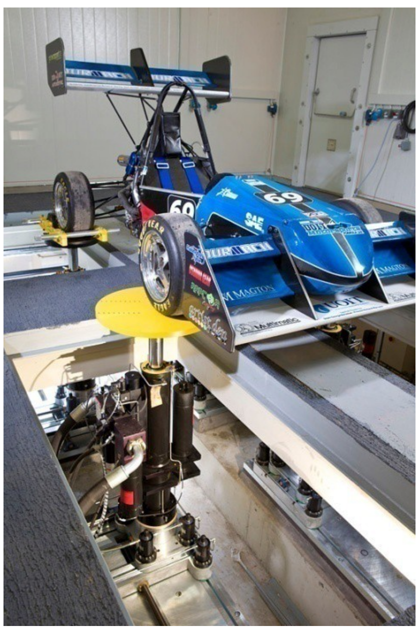
Dry transfer area

4-POST CLIMATE CHAMBER *– Key Features*

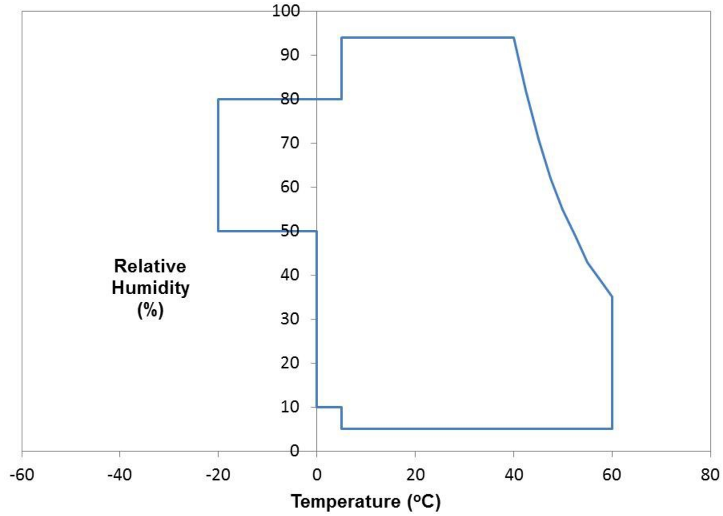
- Drive-on post feature with automatic positioning system
- Temperature from -40°C to +60°C and humidity from 5% to 95% RH
- Dual modes: road load simulation and high flow high-G
- Complete suite of ancillary systems for customer vehicle operation

- ### *Test Section Features*

Overall dimensions	L8.3m x W7.2m x H5.6m
Vehicle entry clearance	W4.26m x H4.49m
Drive-on wheel pans	Remotely adjustable track and wheelbase
Exhaust extraction system	Garage type
Safety	Man-down pull cord
In-chamber power	Outlets for plug-in vehicles



Thermal Performance Specifications



Other performance (measured):

- Maximum cooling rate: +60°C to -40°C in 6 hours
- Temperature uniformity: σ ≤ 1.05 °C over the entire temperature range -40 °C to +60 °C
- Temperature stability: σ = 0.28 °C over the entire temperature range -40 °C to +60 °C

4-Post Shaker Specifications

Manufacturer & Model	MTS 248.05
Control System	Flextest GT w/ 793 system software
Simulation Software	MTS RPC Pro software
Actuator Force	50,000N
Servovalve Flow	11.3L/s
Vehicle types	Passenger car, light duty trucks
Track range	1270mm to 2110mm
Wheelbase range	1572mm to 4572mm
Vehicle weight	4500kg
Range of motion	+/- 150mm
Frequency response	0.5Hz to 50Hz
Maximum acceleration	19.5g to 100g (depending on moving mass)
Maximum Velocity	5m/s

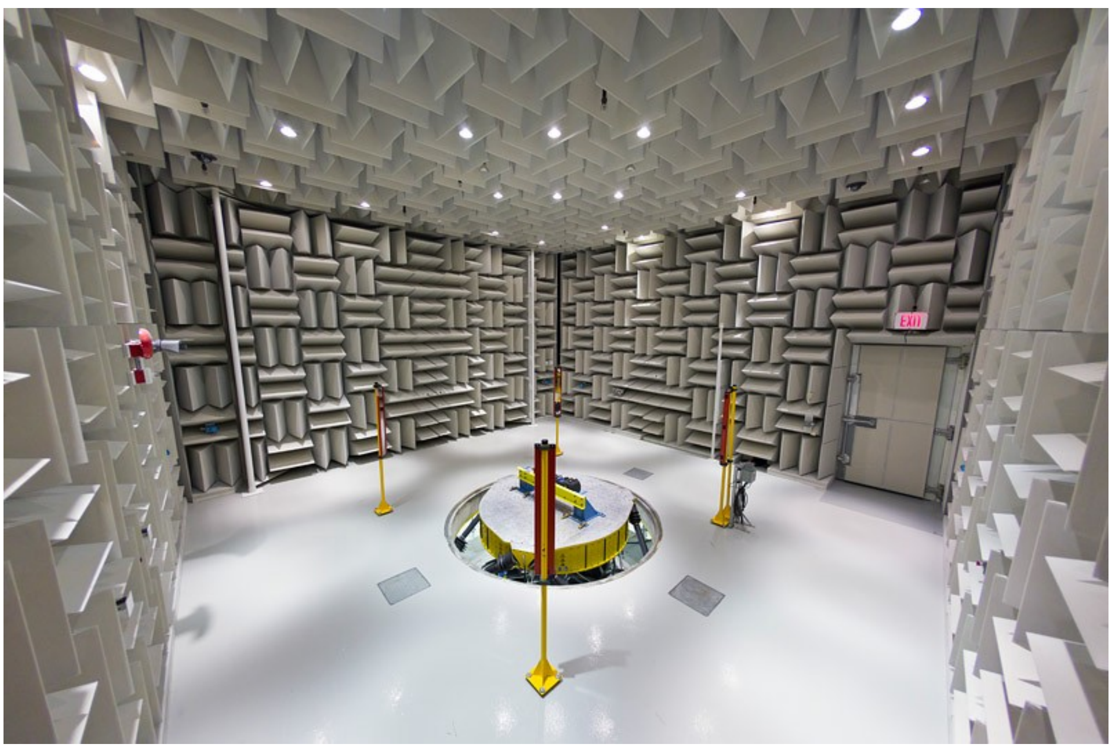
HEMI-ANECHOIC CHAMBER WITH MULTI-AXIS SHAKER TABLE - Key

- *Features*

  - Hemi-anechoic chamber, 150Hz cut-off frequency with exceptionally low background noise
  - 6 degrees of freedom (3 translational, 3 rotational) inverted hexapod hydraulic shaker table

- *Test Section Features*

Overall dimensions	• Inside room surface: L9.00m x W8.87m x H5.15m • Clearance to acoustic treatment: L7.6m x W7.5m x H4.4m
Test object entry clearance	W4.41m x H4.35m
Chamber acoustics	• Cut-off frequency: 150Hz • Background noise level measured to NC-16 with ventilation system operating (<25dB above cut-off frequency)
Pit opening for shaker table	2.77m diameter
Safety	Laser based light screen
Pure acoustic test set-up	Portable cover plates for pit



Multi-Axis Shaker Table Specifications

Manufacturer & Model	MTS MAST Table 353.20
Control system	Flextest 100 w/ 793 System Software
Simulation system	MTS RPC Pro Software
Table diameter	2.0m

Test object max payload weight	680kg
Maximum translation displacements	• Vertical: ±150mm • Lateral: ±120mm • Longitudinal: ±120mm
Maximum rotation displacements	• Pitch: ±8° • Roll: ±8° • Yaw: ±6°
Maximum velocities	• Vertical: 1.0m/sec • Lateral: 0.8m/sec • Longitudinal: 0.8m/sec
Bare table response	• Frequency response: 150Hz • Vertical Acceleration: 17.8 g • Lateral Acceleration: 10.5 g • Longitudinal Acceleration: 10.5 g
Maximum payload response	• Frequency response: 100Hz • Vertical Acceleration: 11.0 g • Lateral Acceleration: 6.5 g • Longitudinal Acceleration: 6.5 g

- Five-floor building connecting the CRF with faculty of engineering building, containing heavy lab areas and industry-university collaborative research space
- Second and third floors are university-sponsored collaborative research areas
- First and fifth floors are secure areas (total area 2,190m^2) containing preparation areas, machine shop, offices, laboratories, conference rooms and common work areas that are available to rent

- *Capabilities*

First floor	• Total area: 731m^2 • Support shop with benches, machine tools, welding and grinding equipment and common use tools and equipment • High-bay heavy lab preparation hall with entry door to outside
Fourth and Fifth floors	• Office space ○ Outfitted with desks and internet ○ Conference room available • Lab space (reconfigurable) ○ Bare heavy lab floor ○ Drop-down power: single phase 120v, single phase 240v, three phase 575v ○ Shop air 125psi ○ Available natural gas and exhaust ventilation connections

Support shop

Abbreviations and Acronyms

Abbreviation	Explanation
AAR	Association of American Railroads
AC	Alternating Current
CFR	Code of Federal Regulations
DC	Direct Current
ESi	Engineering Systems, Inc.
FRA	Federal Railroad Administration
LED	Light-emitting diode
RH	Relative Humidity
TAG	Technical Advisory Committee