Safer Thermographic Inspection of Medium Voltage Electrical Panels on Navy Ships

The National Shipbuilding Research Program

2015 Electrical Technologies Panel Project

FINAL REPORT
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Preface

This final report summarizes research done, test methodology, laboratory test results, field test results, and technology transition path forward as well as the regulatory and safety aspects of implementing this thermographic technology. The final project report is releasable to the NSRP technical community and does not contain any restricted information.

Executive Summary

Installation of shipboard electrical switchgear practices results in loose connections and wiring errors that can lead to unsafe and costly electrical failures including arc faults. Current practices to detect these errors primarily involve infrared thermographic inspection of the open cabinets while under load. Newer ships are moving from 450V panels to 4160V panels and higher, where open panel inspection involves extensive procedures and protective equipment, and in some cases is precluded altogether for safety reasons.

Navy Supervisor of Shipbuilding, Gulf Coast (SSGC) identified this as a major issue. This NSRP Electrical Technologies Panel (ETP) Project was set up to investigate possible solutions. The project had four primary tasks: assess requirements, perform lab tests, perform field tests in a representative three phase 4160V cabinet, and generate recommendations for implementation. Penn State Electro-Optics Center (PSU EOC) was the technical lead, with shipbuilder guidance from Huntington Ingalls Incorporated (HII), and SSGC as the government stakeholder. An Integrated Product Team (IPT) was assembled, consisting of these partners, the Technical Warrant Holder, NSWC Philadelphia Division, switchgear manufacturers, and other interested parties. The period of performance was January 2015 through July 2016.

From what was learned in this project, use of IR windows in electrical panels is a viable way to test for faulty connections. MIL standards currently under revision are incorporating the use of IR windows in these cabinets for this inspection and using the results of this project as guidelines for these requirements. There will be a significant design challenge for switchgear manufacturers to provide line of sight access from windows to all targets without obstruction. The dust boots in these cabinets will also require some determination as to whether to measure the boot or cable and how to best interpret the results. Procedures will need to be revised and new severity criteria (new "star chart") will need to be developed.

PSU EOC conducted a preliminary requirements review and trade studies on different methods of detecting electrical faults in cabinet wiring. Discussions with the IPT and at ETP meetings refined the approach to investigating the use of Infrared (IR) transparent windows in the panel covers to permit thermography through the closed cover, which would allow inspection at greatly reduced risk without the current cumbersome inspection process and permit inspection of 4160V panels in venues where it is currently not performed.

Current practice uses infrared thermography to measure the temperature of electrical connections when under load, which are normally the same across electrical phases. A faulty connection on one phase is hotter than the adjacent phases and will be detected by the thermal camera. Because the actual temperatures vary with load, a comparative test is used. It is the temperature difference between adjacent connections that is important and a guideline chart ("star chart") has been published to correlate the magnitude of the difference with the severity of the fault for 450V cabinets.

There are two basic types of IR windows, known as crystal and polymer, each with advantages and disadvantages. Two crystal windows and two polymer windows were used in laboratory tests. Two infrared cameras were borrowed for testing, including one of the type used by the Navy and one used in shipyards. Laboratory tests were performed at the PSU EOC in Fall 2015 and included tests for accuracy, temperature range, field of view, simulated faults and visible imaging through windows. The rubber dust boots that are required over 4160V connections were also evaluated. Though thermal imaging could be taken through either type of IR window, the crystal windows emerged with a slight advantage. Crystal windows were selected for the field test.

The field tests took place at the DRS Power and Control Technologies facility in Milwaukee, WI in February 2016 using a prototype 4160V cabinet. By energizing the cabinet with low voltage and high current, realistic temperatures could be attained safely, including simulating a fault by loosening a connection. Tests performed included assessing field of view and line of sight through windows, detection of simulated faults, imaging with dust boots in place, and visible imaging through windows.

The field test largely confirmed the laboratory testing, with some additional insight into practical application of the IR windows in an actual cabinet. Major conclusions from all testing include:

- Thermal imaging through IR windows can successfully be done with proper attention paid to camera settings to account for the emissivity of the target and the window attenuation.
- The actual field of view through the window is quite large with the camera placed at an angle. Adjacent phase connections can be framed in the same image. The major issue is internal obstructions such as cables, brackets, and components that limit line of sight viewing from the window to the connections. Future cabinet designs that include IR windows will need to take this into account. This may be a difficult design challenge.
- The dust boots that are required to prevent electrical creep and tracking in higher voltage cabinets definitely affect thermal imaging. Two boot materials were tested and neither was transparent to IR wavelengths. However, convection and conduction beneath the boot resulted in hot spots on the boot surface that could plainly be seen in the thermal images. More investigation is needed to either produce a boot material transparent to IR or determine reliability of temperature measurements on these hot spots.
- Alternately, imaging the cables that exit from beneath the dust boots looks to be a viable method for detecting faulty connections. The heat from the loose connection is transferred down the cable and this is also plainly visible in the thermal images. Again, some additional investigation would be needed to determine how to correlate the temperature of the cable with the severity of the fault at the connection point.
- One of the cameras (Fluke TI10) used by the shipyard for production under current practices did not have the ability to compensate for the attenuation of the infrared radiation through the window resulting in temperature measurements that were too low. This is a caution that cameras used for inspection through windows will need to be able to compensate for this.
- Current practice uses a visible image in conjunction with the IR image to put the measurement in context, since many connections inside a panel are similar. Most cameras include a visible imager for this purpose. With the panel cover on and using an IR window, there is insufficient illumination in the cabinet to take the visible image. Built in camera lamps often cause reflections that obscure the image. Supplementary illumination alongside the lens is required.

1.0 Background

Even under best practices, installation of shipboard electrical systems results in loose connections and wiring mistakes that lead to arc faults and other electrical failures. It is estimated that mistakes exist in 15%-20% of all installations which are unsafe and could cost millions of dollars in downtime and repairs if not detected [SSGC]. Electrical panels and infrastructure are inspected by shipbuilders prior to delivery, by the government prior to sea trials, and again at regular maintenance intervals. Three phase power management and distribution systems of medium voltage (4,160V) are used on LHD, LHA, DDG-51 (FLTIII), CVN, and DDG-1000. The existing method of inspecting electrical infrastructure utilizes Infrared (IR) thermography, typically long-wave IR (LWIR), for comparative analysis within a panel to identify loose connections via thermal 'hotspots'; differential heat buildup resulting from improper electrical connectivity. Current inspection practices for 4160V infrastructure necessitate securing the area with personnel donning full coverage Personal Protective Equipment (PPE) to image inside active (energized) panels, preferably while drawing a high load such as during sea trials. In some instances, thermographic inspection of an open 4160V active panel is precluded for safety reasons.

The ongoing movement in new ship designs to medium voltage systems necessitates a new approach in switchboard inspection to comply with OSHA regulations for stand-off distance of medium/high voltage systems and avoid Technical Warrant Holder (TWH) waiver requests [SSGC]. This project explored options for installation of IR transparent windows in military grade electrical panel covers so that inspections can be made with closed panels, avoiding dangerous proximity to energized circuits and eliminating the need for secured locations, PPE, and waivers. Research efforts were guided by shipbuilder and government stakeholders with consideration to best practices and requirements.

Penn State EOC conducted a preliminary requirements development and trade study. This included investigation of the shipboard electrical systems parameters, inspection of the spatial domain, IR inspection scenarios as well as OSHA standards and industrial hardware for thermal imaging. Besides IR windows, potential solutions with pros and cons of each were identified that included a standalone gantry for remote imaging, temperature sensitive paint, ultrasonic sniffers, and RF interrogation of embedded temperature sensors. Candidate solutions were vetted through NSRP Electrical Technologies Panel (ETP) presentations and subsequent stakeholder interactions. With the support of this community, the approach was refined such that this project focused on installation of panel covers with IR transparent windows enabling safe IR inspection without exposing personnel to energized electrical components.

Current practice uses infrared thermography to measure the temperature of electrical connections when under load. Under normal circumstances, all three phases are at the same temperature, which depends on the level of current. If a connection on one phase is faulty, that connection will be hotter than the adjacent phases and will be detected by the thermal camera. Because the actual temperatures vary with load, a comparative test is used. It is the temperature difference between adjacent connections that is important and a guideline chart ("star chart") has been published to correlate the magnitude of the difference with the severity of the fault for 450V cabinets. Table 1 shows the star chart for 450V cabinets from S9086-RJ-STM-010 NSTM Chapter 504 Revision 7, 1 September, 2012.

Table 504-17-1 ELECTRICAL INSPECTION CRITERIA		
Severity Code	Temperature Rise (ΔT)	Assessment and Action
****	70 °C (126°F) and above	**Failure Imminent.** Equipment should be secured immediately and not operated until repairs are complete
***	40 °C (72 °F) to less than 70 °C (126 °F)	**Failure Almost Certain**. Equipment should be secured if operating conditions permit otherwise monitored until corrective action can be taken.
**	20 °C (36 °F) to less than 40 °C (72 °F)	**Failure Possible.** Corrective action should be taken as soon as feasible.
*	5 °C (9 °F) to less than 20 °C (36 °F)	**Performance Degraded**. Corrective action should be taken at next scheduled routine maintenance period or as schedule permits.
N/A	Less than 5 °C (9 °F)	**No corrective action required**; note for future reference
NOTE: The temperature rises or ΔT's indicated above are the temperature differentials between the thermal anomaly (i.e., faulty connection or component) and the reference temperature. The reference temperature should be a similar, normal operating connection, component, or phase. Decision regarding repair priorities and order of maintenance should be determined by the magnitude of the temperature differential and the critical nature of the equipment or system involved.		

Table 1 Inspection Criteria for 450V Electrical Panels

2.0 Overview

This project explored the use of IR transparent windows in electrical panel covers so that inspections can be made with closed panels, avoiding dangerous proximity to energized circuits and eliminating the need for secured locations, PPE and OSHA waivers. IR windows embedded in panel covers would allow inspectors in the room to operate at any time before/during acceptance/sea trials at greatly reduced risk and without PPE, while utilizing the same cameras and practices currently used but without the cumbersome and costly need to secure the area and de-energize and re-energize electrical switchboards. The project conducted laboratory tests of different IR windows and culminated in a proof of concept test / demonstration with final results including characterization of cabinet connection inspection via installation of switchgear panel covers with IR transparent windows. Findings are relevant to switchgear manufacturing, shipbuilder construction and government applications where inspection of electrical switchboards and transformers is necessary.

Penn State EOC led technical development with Ingalls Shipbuilding guiding efforts with respect to shipbuilder applications and best practices. Naval Sea Systems Command's Supervisors of Shipbuilding, Gulf Coast (SSGC) was the first to identify this issue as a major problem for their electrical inspections and acceptance at sea trials. SSGC participated as the government stakeholder, providing guidance and oversight towards implementing a practical solution for government applications. This project was supported by the Technical Warrant Holder (Electrical Systems, the Naval Systems Engineering Directorate, SEA05) with representatives from the Naval Surface Warfare Center, Philadelphia (Code 427 - Propulsion and Power Systems and Code 429 - Advanced Electrical Systems) providing significant guidance and contributions. Industry participation included DRS Power & Control Technologies, Inc as well L3 SPD Electrical Systems. DRS provided use of their testing facilities and use of a mockup of a medium voltage switchgear panel for final testing/demonstration. L3 provided a protective rubber boot and general counsel throughout laboratory testing. Advisors/stakeholders and other contributing parties are listed in the *References*, sections 6.1 and 6.2.

Applicability and transition with respect to shipbuilding practices, environments, and Mil-specs were examined. Laboratory tests to evaluate thermal imaging through IR windows under controlled conditions and to compare the two main types of available windows (crystal and polymer) were first conducted by Penn State EOC. See section 3.1, *Laboratory Tests of IR Cameras and Windows* for a summary of results with the full-up *Laboratory Test Report* included as *Appendix A*. Characterization of a representative scenario can be found in section, 3.2, *Proof of Concept Demonstration – Field Test with Medium Voltage Switchgear Mockup - Summary*, with the complete *Field Test Report* attached as *Appendix B*. The transition of IR windows for U.S. Navy use is discussed; section 4.0, *Technology Transition: MIL-DTL Requirements.* Perspectives from Supervisor of Shipbuilding Gulf Coast regarding the business case and implementation of IR windows are included in this document; section 4.1, *Navy Supervisor of Shipbuilding Gulf Coast Perspectives [SSGC]*. Ingalls Shipbuilding perspectives regarding shipbuilder implementation of thermal imaging windows into medium voltage switchgear is also included; section 4.2, *Thermal Imaging Window Integration – Shipyard Impacts [Ingalls Shipbuilding]*. Final *Recommendations*, are included in section 5.0.

3.0 Test Results & Conclusions

Several commercially available IR windows were examined in laboratory tests conducted at the Penn State Electro-Optics Center facility in the Fall of 2015. Using the results of these tests, a certain type of window was selected and two sizes of that window were evaluated in a field test conducted at the DRS Technologies, Inc. factory in Milwaukee, WI in February of 2016.

3.1 Laboratory Tests of IR Cameras and Windows - Summary

The objective of this testing was to evaluate thermal imaging through IR windows under laboratory conditions and to compare the two main types of available windows: crystal and polymer. It was not the intent to determine if IR windows work for infrared thermography. They are sold as a commercial product for that purpose. Rather it was to set up some baseline measurements to determine how the windows affect the temperature measurements and to ascertain how their performance might impact a shipboard thermography inspection.

Most of the tests were conducted using a blackbody radiation source as a repeatable heated target. This helped establish the baseline performance. The last few tests used representative cables and bus bar heated to different temperatures to simulate a panel inspection with a wiring fault. Two thermal cameras were used and four IR windows were evaluated. After initial testing, this selection was reduced to one camera and two windows, one crystal and one polymer. Multiple tests were run, and are as described in the report. The complete *Laboratory Test Report* can be found in Appendix A. A spreadsheet listing windows and cameras examined in this project can be found in section 6.4, *IR Windows and Cameras Reviewed*.

The most significant findings from the laboratory experiments were:

1. Reasonably accurate temperature measurements can be made through IR windows provided attention is paid to emissivity and transmissivity settings in the camera. Some small variation in transmissivity settings from day to day would need to be accounted for when developing procedures for practical tests.
2. Variations in target (cable lugs) surface geometry and condition make the measurements very sensitive to the location of the measurement point in the image. The Navy accounts for this by using a common emissivity setting for all tests and noting that it is temperature difference between adjacent phases in the connection that is important rather than the absolute temperatures. These issues can be minimized by developing uniform techniques and procedures to provide a useful comparison test.
3. The windows provide an extremely wide horizontal and vertical field of view allowing visual access to most of a cabinet through a single window, limited only by internal obstructions. This will allow more flexibility in the placement of the window(s) in the panel and the use of fewer or smaller windows.
4. The polymer windows all have a reinforcement grid behind the viewing surface. This is evident in the imaging but does not affect the thermal measurements in a significant way. However, it does reduce the field of view compared to the clear crystal window and it affects visible images taken through the grid. Some polymer windows are translucent,

which precludes taking visible images at all. Crystal windows are recommended for this reason.

5. The rubber boot material that covers the connections in recent panels does affect the measurements between connections at different temperatures. However, sufficient differences can be seen in the temperature of the boot over the connection and in the cables as they exit the boot to indicate that one connection is significantly hotter than the other.
6. Reflected glare off both window types affects visible images taken with the camera's own illumination source. As the intent of the window is to allow viewing with the panel cover closed, some other method of illuminating the interior will be needed.

Subsequently, there was an open question about the supposed degradation of crystal IR windows over time due to the absorption of moisture. Penn State EOC examined this issue further and evidence suggests that the durability and longevity of crystal windows are such that they can be used on Navy ships without reservation. Degradation is very small, even under extreme conditions and they pass the relevant vibration and shock tests. Either type of window could be made to work, but advantage goes to the crystal window. It has better field of view, much better ability to take visible images and has already passed Navy vibration and shock tests. The complaints about the crystal windows (bandwidth roll-off and degradation over time due to moisture) do not affect the testing and durability of the crystal windows. The details of the arguments are listed in section 6.3, *Relative Merits of Crystal vs. Polymer IR Window*.

3.2 Proof of Concept Demonstration – Field Test with Medium Voltage Switchgear Mockup - Summary

The purpose of these field tests was to determine the effectiveness of IR windows in a representative shipboard electrical panel and identify issues that would be relevant in this setting. Members of the Integrated Project Team and other stakeholders were on hand to observe the tests and provide perspectives. DRS had built a prototype 4160 Volt cabinet of the type relevant to this project and offered it as the test fixture along with their testing facility. In this facility, the cabinet was energized with low voltage, high current to simulate the temperature build up at the connections inside the cabinet. A benefit of this method was that faulty connections could be simulated by loosening a cable connection. This would not have been possible on a cabinet energized at 4160V due to concern of a potential arc fault.

Two different IR crystal window sizes were used, along with two different thermal cameras. DRS had provided the prototype cabinet with a fixture on the back that permitted the IR windows to be placed in various locations. Both infrared thermal imaging and visible imaging (for context) through the windows were performed. Tests were also performed using samples of the dust boot material that is installed in every 4160V cabinet to protect the connections from buildups of dirt and grime that can lead to short circuits.

The most significant things learned were:

1. Thermal imaging through windows in a panel can be done with proper attention paid to camera settings. Normal and faulty connections were imaged with faulty connections plainly evident by the higher heat produced across the connection compared to normal connections.

2. Thermal imaging through windows is fundamentally not much different than imaging through an open panel cover. However, adjustments to procedures will need to be made. The most significant issue is setting the camera to compensate for the attenuation of the light through the window. Other practical issues regarding how much can be imaged through the field of view and the necessity of supplemental illumination also need to be taken into account. New procedures will have to be developed for practical tests to account for these factors, including a new "star chart" for reference to severity of fault conditions. Some of the thermal imaging cameras have features that might be helpful when developing new procedures, such as multiple measurement areas, difference measurements, and annotated reports generated in the camera.

3. Internal obstructions are the biggest issue for imaging through windows. By angling the camera to the window, the field of view is sufficient to see anywhere in the cabinet from one window in the top and one in the bottom, were it not for internal obstructions. Cables running from the bottom to connections at the top and the brackets that hold them can obscure connections near the bottom. The nature of the bus bars (vertical between cabinet halves and horizontal between cabinets) mean that some connections will be obscured.

   This will be a design challenge for the cabinet manufacturer, to minimize the number of internal obstructions and optimize the placement of the windows. It may be more advantageous to include more windows to provide better line of sight to all internal connections.

4. The dust boots that cover all connections within the 4160V cabinets definitely affect thermal imaging. Two dust boot materials were tested, but neither was designed for this particular cabinet. The existing boot materials are not transparent to infrared wavelengths. Therefore, detecting a faulty connection requires that the heat from the connection be transferred to the boot, and then the hot spot on the boot surface can be measured.

   In this case, proper fit and location of the dust boot makes a difference. The more air gap there is between the connection and the boot surface, the less heat gets transferred. The most evident hot spots in the thermal images were where the boot material was very close or touching the hot connection. Design of new boot covers that are transparent to IR wavelengths is an area worth further investigation.

5. Alternately, given that it will be hard to tell how much heat is being transferred to the boot material, it may be better to image the cables as they enter or exit beneath the dust boot. The cables have a more uniform emissivity than the connections themselves. The dust boots can be designed so that the cables exit from the boot not far from where the cable lug is bolted to the bus bar. These tests show that the cable to a faulty connection is considerably hotter than adjacent cables with good connections and well evident in the thermal images. Some additional research would need to be completed to determine the

amount of temperature loss down the cable, so as to get reliable temperature measurements and redefining the criteria in the "star charts". If this method is chosen, then it would be better to select window locations in the panel cover that afford view of the cables rather than the connections themselves, which will be covered by the boots.

6 While it may be desirable under production circumstances to use a simpler IR camera with fewer features, the camera should at least have the ability to account for the transmissivity of the window. Otherwise, the reported temperatures will be too low by a large margin (as seen in the Fluke TI10 images) and the differences between faulty connections and normal connections may not be large enough to generate an error condition.

7 Supplementary illumination will be needed to take visible images for context with the IR images. With no illumination at all, the interior of the cabinet is too dark for visible photography. The built in lamp with the camera sometimes allows adequate pictures but often creates a reflection on the window that obscures part of the image.

Best results appeared to be when an auxiliary light (flashlight) was shown in the window adjacent to the camera lens, or through another opening nearby. That opening could be a second IR window, if it was deemed necessary for avoiding line of sight obstructions. A lamp through a window at the top of the cabinet was inadequate to illuminate the target at the bottom of the cabinet and vice versa. Lighting built into the cabinet would solve the problem, but that would be a design issue for the manufacturer.

The practical tests mostly confirmed what was learned in laboratory testing. See *Laboratory Test Report*, *Appendix A*, for more information. Refer to *Appendix B* for the complete *Field Test Report*.

4.0 Technology Transition: MIL-DTL Requirements

With the goal of enabling safer IR inspection of electrical panels on Navy platforms, this project was supported by the Technical Warrant Holder; Electrical Systems, The Naval Systems Engineering Directorate, SEA05. As such, the information gained from this project is directly impacting shipboard requirements for the next generation of medium voltage switchboards through MIL-DTL-32483A (medium voltage switchboards, hard-mounted) and low voltage switchboards through MIL-DTL-XX653 (low voltage switchboards, shock-mounted). Section 4.1, *Navy Supervisor of Shipbuilding Gulf Coast Perspectives [SSGC]*, includes proposed specifications to be added MIL-DTL-32483A & MIL-DTL-XX653. As additional switchboard/enclosure specifications become available for update, they will also invoke similar requirements with the basis of these requirements being derived from this project.

IR windows can be implemented in military ships to facilitate better inspection practices and procedures which are not only safer but also reduce costs. IR panels embedded in panel covers would allow inspectors in the room to operate at any time before/during acceptance/sea trials at reduced risk and without PPE, while utilizing the same cameras and practices currently used but without the cumbersome and costly need to secure the area and de-energize and re-energize electrical switchboards. These changes should minimally impact shipyard processes with updates to testing processes and training needed for full implementation.

The path to permanently installed IR windows on Navy ships is attainable in the near term. Industrial implementation of IR windows is ongoing. Commercial IR windows are currently available including some crystal IR windows which have already been qualified against mil-standard shock and vibe tests. Code 954 (Shipboard Sensors and Instrumentation Branch) out of the Naval Surface Warfare Center, Carderock Division (NSWCCD SSES Philadelphia) executed shock and vibration testing, qualifying a set of IR inspection windows; 3” and 4”. Their vibration and shock test reports - *“MIL-S-901D, Lightweight, High Impact (H.I.) Shock Test Report”* (No. NSWCCD-954-STR-172) and *“MIL-STD-167-1A, Mechanical Vibration Test Report”* (No. NSWCCD-954-VTR-172) - are available upon request through NSWCCD. IR cameras are not only advancing in terms of the inherent technology (resolution and FOV), user friendliness and feature sets are improving. Additionally, the cost of IR imagers has decreased significantly in the past 10 years. The trend of improved performance/usability and decreased cost should continue. A spreadsheet listing windows and cameras reviewed in this project can be found in section 6.4, *IR Windows and Cameras Reviewed*.

4.1 Navy Supervisor of Shipbuilding Gulf Coast Perspectives [SSGC]

Business Case

Thermal imaging devices can likely be found on most US Navy ships. In the past, these devices were cost prohibitive, difficult to operate, and typically, required a specially trained individual to perform the inspections. Today, these devices are small, easy to operate, and affordable. Thermal imaging devices have almost limitless applications, but their primary application or intent onboard US Navy ships relates to electrical enclosure inspections.

During new construction, overhauls, and deployment, periodic electrical inspections are performed using thermal imaging devices. As long as the electrical enclosure is powered, the inspector can perform an inspection on the enclosure. This inspection typically requires the cover to be removed to allow the imaging device to see inside the enclosure. In general, the inspections evaluate temperature differences on various phases per circuit. If a temperature difference is discovered, it is a good indication of a potential problem due to the unlikelihood of varying temperatures on different phases of the same circuit. If not corrected, over time, it will likely cause a mishap. Because most of the electrical items onboard a ship are 450 volts or less, this can be safely accomplished just as long as the inspector does not cross the plane of the equipment with the imaging device.

The value has long been appreciated for using thermal imaging devices onboard US Navy ships to evaluate 450 volt or less electrical equipment. In recent times, US Navy ships are transitioning to medium voltage generation and distribution (4160V). OSHA requirements, US Navy requirements, and overall concern for safety has resulted in minimum thermal imaging inspections being utilized on medium voltage equipment. Other methods such as ultra-sound have been used to detect loose connections in medium voltage equipment, but limited success has been achieved.

Knowing the value of thermal imaging, the team found it has the most beneficial means to accomplishing detection of loose connections on medium voltage equipment if we could provide a safe and effective means. This was accomplished with the implementation of Infrared Windows integrated into equipment which will allow thermal imaging to be accomplished safely while eliminating the financial and logistic concerns related to the inspections.

- **Eliminates the inefficient and manpower extensive inspection, which require NAVSEA 05Z3 instruction/permission:** In accordance with NSTM Chapter 300, if a thermal image inspection for equipment greater than 1000 volts is required on a US Navy ship, it requires a written instruction from the NAVSEA 05Z3 Technical Warrant. This permission typically requires extensive effort to produce. The method in which the inspection will occur has to be explained along with outlining the equipment being used (IR device, arc flash suites, etc.). Because some of the equipment is in tight locations, special tactics may be required. If permission is granted to perform this type of inspection, it will likely not be accomplished while the ship is underway due the potential movement of the ship causing a concern for safety. In addition, it is a massive undertaking to remove the covers for this equipment. For example, the crew would likely be required to tag-out the equipment which often takes extensive time to complete. Once tagged-out the covers will be removed and the area will be secured (i.e. roped off). Once the area is secured, the crew would clear the tags followed by re-energizing the equipment with covers removed to begin the inspection. When the inspection is over, the crew would be required to follow the same tag-out process to re-install the covers. This is not only time consuming, but very disruptive to the entire ship, since loss of power is likely and will likely prevent others on the ship from performing their missions. Because this is so disruptive it will likely occur really late in the day or at a time to minimize disruption. However, during the times typically allowed to perform this disruptive test, the load on the equipment being tested is likely to be really low. Due to the aforementioned factors, there is a chance some issues may not be able to be detected using the Thermal Imaging device.

- **Allow inspection any time:** The Infrared Windows will allow inspections to occur at any time, under any condition while minimizing the impact of the inspection to the ship and the crew. With the IR windows, the inspection can occur in the optimal time such as while the ship is underway with full load on the ship. Having a realistic load will draw the nominal current for the equipment being inspected resulting in more likely identifying a problem if one exists.

- **Reduce manpower:** The amount of individuals required to perform an inspection is minimized. With the IR windows, there is no need to tag-out the equipment, secure the area or disrupt others not involved. There are no special requests/waivers to write and no special safety procedures (other than standard ones already in place) required to be created.

From all aspects, the installation of Infrared Windows will be beneficial. The windows will help reduce catastrophic failure by easily allowing more inspections to occur. With Infrared Windows, the inspections can occur at the optimal time such as while the ship is underway where realistic loads will be present on the system. The IR windows will minimize the impact to the ship and the crew. This benefits the ships and crew by minimizing down time as a result of these preventable failures. The reduction of manpower, the elimination in Headquarter administrative oversight, and the likely prevention of catastrophic failures make installing IR windows in medium Voltage equipment a logical decision. While the integration costs of IR windows into existing equipment could be expensive, the focus of the IR windows should be for any new medium voltage or even low voltage equipment. These windows should be required from conception which eliminates integration cost. This will allow all qualification tests of new equipment to be completed with IR windows. In a short period of time, the US Navy would have IR windows in most of their equipment and like the commercial industry, would start realizing the cost savings from decreased equipment damage, reduced manpower, and logistics.

Implementation – Proposed Specifications

The results from the project through research, lab testing, and test evaluations have resulted in a great deal of information being acquired. Not only have we shown IR windows will provide value with inspecting electrical enclosures (including cable connections and bus joints), but will allow us to accomplish inspections with minimum personnel while minimizing impact to others close to the inspection locations. The information gained from this project is directly being implemented on the next generation of medium voltage switchboards through MIL-DTL-32483A (medium voltage switchboards, hard-mounted) and low voltage switchboards through MIL-DTL-XX653 (low voltage switchboards, shock-mounted). As additional switchboard/enclosure specifications become available for update, they will also invoke similar requirements with the basis of these requirements being derived from this project.

Figure 1 below shows proposed language on thermal imaging specifications being added to MIL-DTL-32483A. Similar requirements will be added to MIL-DTL-XX653:

Proposed Revision

3.4.2.17 Thermal imaging windows and assemblies. Thermal imaging windows and assemblies (housing and cover) shall be provided to view as many cable and bus bar connections as possible. Thermal imaging windows and assemblies shall meet the following requirements as applicable:

a. Thermal imaging windows shall incorporate specialty lenses with broadband transmission allowing both visible spectrum wavelengths and the infrared wavelengths to transmit through the optic (infrared window) thereby allowing the enclosure components to be viewed by both visual means (eyes, digital photographic camera, etc.) and a thermal imager (8.0 to 12.0 microns).

b. Thermal imaging windows shall allow the beam of a flash lamp/light to pass through for visual inspections.

c. Thermal imaging windows shall be manufactured from a clear, rigid, solid crystalline material (calcium fluoride) or equivalent and have no embedded, nor affixed to, grill, mesh, or reinforcing screens in/on the window material.

d. During direct axis or off axis viewing of components within the enclosure, thermal imaging windows shall exhibit a decrease in the measured temperature of no more than 5% at an off axis angle up to 50 degrees.

e. Thermal imaging windows shall be manufactured to be resistant to moisture penetration at face and circumferential edge. Thermal imaging windows shall be subjected to humidity testing in accordance with MIL-STD-810G, Procedure II (Aggravated Cycle), for a period of 10 cycles. At the conclusion of the tenth cycle, the window shall exhibit a change in its transmissive quality of no more than 3% of the original value when tested at off-axis angles of 0 and 50 degrees.

f. Thermal imaging window assemblies shall be supplied with a silicone, or equal, gasket which shall be installed between the outer face of the enclosure and the thermal imaging window assembly unit.

g. The actual viewing aperture diameter of the thermal imaging window shall be no less than 3.5 inches (89 mm) +/- 0.10 inches (2.54 mm).

h. Thermal imaging window assemblies shall have a permanently attached and hinged solid metal impact and load resistant cover secured or opened for viewing access by a single non-removable fastener. To protect from possible arc flash, the metal cover shall be able to remain in the closed position when the thermal imaging window is not being used for viewing.

i. Thermal imaging window assemblies shall be constructed of stainless steel, aluminum, or other high strength metal alloy and have a UL50/NEMA Environment Rating of Type 4/12.

j. Thermal imaging assemblies shall meet arc flash testing of 5kV, 50kA for 30 cycles at 60Hz in accordance with IEC 62271-200.

k. Thermal imaging windows and assemblies shall be rated to 250 °C or greater and shall have a pull out strength of 3600 lbs. or greater when installed.

l. Thermal imaging windows shall not become adrift during switchboard first article testing.

3.4.2.17.1 Number and location of thermal imaging window assemblies. A minimum of two thermal imaging window assemblies shall be installed in each vertical unit of the switchboard as specified (see 6.2). Thermal imaging window assemblies shall be installed in locations that meet the following requirements:

a. Shall be mounted on the rear of each vertical unit of the switchboard and as close as possible to the vertical centerline of each vertical unit of the switchboard.

b. Shall be mounted to provide an unobstructed clear view during direct axis or off axis viewing of bus and cable connections.

c. Shall be mounted to maintain required creepage and clearance distances from electrical conductors and components.

d. Shall not interfere with venting slots/ports.

3.4.2.17.2 Thermal imaging window assembly label. A label shall be provided near each thermal imaging window assembly stating the following:

"Metal cover for thermal imaging window shall only be opened when required for testing or viewing. Otherwise, the metal cover shall remain closed and secured by means of the non-removable fastener."

The label shall also include the recommended thermal imaging camera transmissivity setting as specified (see 6.2) to maximize accuracy of readings taken through the thermal imaging window.

Figure 1. ***Proposed Thermal Imaging Window Requirements Being Added MIL-DTL-32483A. Similar Requirements will be added to MIL-DTL-XX653. [NSWC]***

4.2 Thermal Imaging Window Integration – Shipyard Impacts [Ingalls Shipbuilding]

Background & Shipyard Inspection Processes

The objective of this section is to provide a summary of shipyard perspectives regarding implementation of thermal imaging windows into medium voltage switchgear. Thermography is used to inspect shipboard electrical equipment during ship construction and at regular maintenance intervals on U.S. Navy surface combatants. Typical areas of interest are the shipyard electrical connections into the switchgear and bus bar connections. Thermal inspection helps to identify loose connections that, if not detected and corrected, could cause catastrophic damage to the equipment and impose safety hazards to crew members. This type of inspection is most meaningful when the system is at high demand; therefore, typically conducted during sea trials. To conduct the inspection, existing practices require that the switchgear panel cover be removed to reveal the connections of interest. After the panel cover is removed, an individual will inspect the equipment with a thermal imager (IR Camera). For surface combatants, this is currently only conducted on low voltage (450V) switchgear. Inspections on medium voltage (4160V) switchgear are not presently conducted by the shipyard due to safety issues with removing the panel cover in confined shipboard spaces.

This NSRP Panel Project identified and evaluated safer methods to inspect higher potential systems. The Project Team focused on the use of infrared (IR) windows that could be installed in switchgear panel covers; thereby allowing visual inspection into the equipment with a sufficient safety barrier between the worker and the electrical connections.

Equipment is received in the shipyard and undergoes initial receipt inspection at a land based test facility. Following the inspection, equipment is protected and transported to the ship for installation and electrical hook-up processes. Following installation, the equipment is groomed and at a later stage energized. Thermography testing is conducted as part of the Electric Plant Infrared Survey to verify all electrical connections are secure and the system is ready for delivery. As noted previously, these thermal inspections are conducted on 450V boards only, as a safe inspection method for medium voltage (4160V) equipment is not currently available.

Inspections are done on low voltage (450V) equipment as standard practice. This process includes removal of the panel cover, exposing the electrical connections of interest. With the system at high load, an IR survey is conducted. This series of testing is conducted during Builders Trials, Acceptance Trials, and as needed throughout the ship construction process. Additionally, the U.S. Navy conducts this type of testing after delivery at regular maintenance intervals.

Technology Need & Design Impact

A safe method of medium voltage switchboard inspection is needed to be compliant with future ship requirements. MIL-DTL-32483, "Detail Specification for Medium Voltage Hard Mounted Switchgear", requires thermal imaging windows to be installed in switchgear. To support existing shipyard processes and facilitate a smooth implementation, the following should be considered:

- Reporting Requirements
- Window Location
- Test Equipment Impact
- Training Needs
- Process Changes

The windows should allow transmission of both IR (8 – 12 micron) as well as visible (400 – 700nm) wavelengths. The ability to conduct thermal scans and document areas of concern via digital photography is also needed for documentation and corrective action processes.

To aid in the equipment design selection and procurement process, window details should be specified to include window materials, size, and location. Testing conducted in this project determined that clear crystal windows are needed to achieve optical performance in the visible and IR spectrum of interest. A minimum window size of 4 inches is recommended to maximize view angels and enable suitable access for IR camera lens. Location and quantity of windows per cabinet is dependent on the specified areas of interest (joints and connections to be defined by ship specification) and interior layout of the equipment. It was determined that a minimum of two windows is needed for viewing access and to accommodate an external light source needed for visible photography.

The window locations should consider not only the areas of interest, but also the as installed position of the equipment and personnel accessibility. Given limited clearance between the equipment and bulkhead, personnel access may be limited and not conducive to inspection through windows located at the extreme low or high positions on the equipment. Notionally, the windows should be located such that an individual can view and conduct the required infrared survey from a standing position (e.g., kneeling down or standing on ladder not required).

Conclusion & Recommendations: Shipyard Impact

Potential impacts at the shipyard level will include changes to processes, test procedures, and test equipment. Formal processes, including cable routing within equipment will be updated to accommodate line-of-sight access to connections through thermal windows. Test procedures will be updated to accommodate new test methods and test instrument settings. Transmission characteristics of the thermal window material selected and emissivity of the area of interest (e.g., bolt connection, cable jacket, and dust boot) should be included in updated test procedures to achieve accurate results. Test equipment settings will be reviewed to ensure adjustments can be made to compensate for testing through thermal windows.

New methods of inspecting medium voltage switchgear are needed to reduce risk of equipment damage and ensure personnel safety during the inspection process. This project evaluated thermal imaging windows that could be installed in switchgear cabinets. Laboratory testing provided information to aid in window selection, location, and test equipment needs. Minimal impact to shipyard processes is anticipated; however, some training and testing process updates will be needed upon implementation.

5.0 Recommendations

Based on findings in the project, this section includes:

- Recommendations for Cabinet Manufacturers and Shipyards
- Recommendations for Specifications, Standards and Procedure Developers
- Potential Future Work

5.1 Recommendations for Cabinet Manufacturers and Shipyards

1) Current Mil specs are being revised to include requirements for manufacturers to incorporate IR transparent windows into future designs of 4160V cabinets.

2) Manufacturers will need to provide line of sight to all areas of interest. The shipyards are primarily interested in testing the connections made to the cabinets at installation. However, after the ships are in service, the Navy is also interested in testing all connections, including connections made at the manufacturer's factory, as there is the possibility that these also could loosen over time. Providing line of sight from windows to all of these connections represents a design challenge for the cabinet manufacturers, as currently, some of the installed bus bars obscure other connections beneath them.

3) There is currently no requirement for shipyards to route cables away from line of sight from the windows whenever the cabinets are installed. The shipyards should take line of sight from the windows to all points of interest into account when installing cables into the cabinets. Cabinet manufacturers can make recommendations or provide fixturing that ensures this. The Navy could consider including this in the specification for installation of the cabinets.

4) The dust boots required in 4160V cabinets obscure the connections being examined and are not transparent to infrared wavelengths. Manufacturers should investigate whether there is a material that can pass IR radiation and also meet the other requirements for the dust boots. At first look, this does not seem likely, but some IR windows are made of polymer materials that may be suitable. As the boot does not need to provide structural integrity as a window would, there may be additional options. Cost will be a factor.

5) Should a suitable material not be found, manufacturers should take into account how the thermal imaging can be done with the boots in place. The boots should be designed to fit as close as possible to the connections they cover, touching them if feasible. The boots should not cover more material than is necessary to fulfill their function, as it is possible to image on cables or bus bars outside of the boot material due to heat from a faulty connection being transferred along the cable or bus bar. See Procedures below.

6) Shipyards and the Navy will need to ensure that the cameras used in these inspections have the ability to compensate for the window transmissivity. A wide angle lens is not required unless it is necessary to view all three phases of a circuit at once. A standard lens will allow adjacent phase connections to be viewed in the same image.

7) Manufacturers should consider illumination ports or interior lighting to assist in taking visible images through the windows. A supplementary light such as a flashlight alongside the camera lens in the same window was seen to be effective in the field tests, but it is awkward and not always easy to align. Permanent lighting or an auxiliary port for an external light would help. However this would be a tradeoff between costs to implement and perceived benefits in the inspection.

5.2 Recommendations for Specifications, Standards and Procedure Developers

1) Current Mil specs are being revised to include IR windows in 4160V and other cabinet designs. These requirements should take into account some of the factors regarding IR windows that were learned in this project, namely:

    a) Larger windows will provide a more efficient inspection in that visible and infrared images can be taken simultaneously and there will be less need for camera measurement adjustments from target to target. Larger windows also permit auxiliary lighting for visible imaging to be used in the same window as the camera.

    b) Line of sight to areas of interest from the windows should be maintained in the design of the cabinets. The areas of interest should be identified.

    c) Cable routing during installation should not obscure line of sight from the windows.

    d) It might be better to place the windows so that they provide imaging of the cables rather than the connections, which will be obscured by the dust boots (see Procedures below).

    e) Allow for innovation on the part of the cabinet manufacturers to permit meeting line of sight by alternate means. For example, use of moveable windows rather than installing multiple windows, provided all other requirements are met.

    See section 4.1, *Navy Supervisor of Shipbuilding Gulf Coast Perspectives [SSGC]*, for more details.

2) Procedures will need to be developed for doing thermographic inspection through IR windows. This will involve several factors:

    a) Key will be the camera transmissivity setting to account for the window material.

        i) Different window materials require different transmissivity settings. This may be an argument for uniformity in window material, to avoid erroneous settings when moving from one type of window to another.

        ii) Transmissivity can be determined for each window and that setting recorded on the metal cover of the window. The inspector can read the setting from the cover and enter it into the camera, for maximum accuracy.

iii) However, since a comparative test will still be used, it is likely not necessary to have maximum accuracy for the absolute temperature measurements. Instead, a common transmissivity setting can be determined for all windows of that type and that setting written into the procedure. The lower the setting, the more the light is attenuated by the material, so a setting low enough to encompass all windows of the same type would err on the safe side. That is, recorded temperatures through a window with better transmission would be slightly higher and the fault condition more evident, than if the temperatures were lower. Similar to the Navy's setting of emissivity, this uniform setting accepts some false positives while avoiding false negatives.

iv) It has been determined that the degradation of crystal window materials over time due to moisture absorption is small and not likely to impact a comparison test. Nevertheless, it is recommended that a procedure be developed to test transmissivity on a periodic basis to verify that attenuation has not increased beyond acceptable levels. This could be done once every several years by imaging a heat source at a known temperature through air, then through the window with the transmissivity adjusted in the camera. If the temperature difference between the two tests exceeds a determined amount, the window should be replaced. This could be done during some other routine maintenance with the cabinet de-energized and using a portable known heat source.

b) These tests have shown that the dust boots required in 4160V cabinets are not transparent to infrared light and instead, the heat from a faulty connection below the boot is evidenced by a hot spot on the surface of the boot. While it has been seen that a hot spot definitely indicates a problem below the boot, the extent of that problem could not be determined. The hot spot temperature is dependent on the air gap between the connection and the boot material, naturally having the best conduction when the boot is touching the connection. However, the heat transfer through the boot would have to be determined and would likely vary for different boot materials (from different manufacturers) and for different boot geometries. Any procedure will need to take this into account if it is desired to measure the temperature of a hot spot on the boot surface to determine the severity of a bad connection.

c) An alternate to imaging the surface of the boot was seen in that the temperature of the cables as they exit the boot are also indicative of a loose connection beneath the boot. The emissivity of the cables imaged in both the laboratory and field tests was quite uniform, so procedures for imaging cabinets with the dust boots could direct the inspection to be of the cables rather than of the boots. The amount of heat transfer down the cable would need to be determined in order to develop reasonable standards on the extent of the temperature differences at the cables that would generate a corrective action.

d) In current thermographic inspections of 450V cabinets, the temperature difference between phases in the same circuit are compared against an inspection criteria chart that dictates the action to be taken depending on the severity of the temperature difference. This is known as the "star chart" as found in S9086-RJ-STM-010 Chapter 504, Table 504-17-1. For inspection with IR windows, this chart will need to be revised, due to two factors. First, if a common transmissivity setting is used, the temperatures and hence the difference temperature will be biased upward. This is similar to what is already done with emissivity, but adds another factor. Secondly, once a determination is made to image on the boot surface or on the cable surface, the heat transfer to these surfaces from the actual bad connection will need to be taken into account when making the new chart.

e) Camera emissivity is another setting that may need to be determined for new procedures. Currently the Navy specifies that the camera emissivity be set to 0.8 for all tests. This removes uncertainty and provides uniformity between operators and tests taken over time. Also, in the current testing, the bolts and cable lugs are imaged directly. These surfaces present variable emissivity to the camera, as they have non-smooth surfaces and are relatively reflective. Imaging on the boot material or cables would simplify the emissivity setting, but would also have to be worked into the procedure.

f) A camera that has the ability to set emissivity and transmissivity typically has the ability to set other parameters as well. These include atmospheric temperature, object distance, relative humidity and apparent reflected temperatures. Generally speaking, for a short range test such as this in a controlled environment, these factors do not influence the test results by much, but they should be included in a procedure so as to not introduce another variable.

g) If it is desired to take a visible image simultaneously with the infrared image to provide context, then procedures should include a caution to the operator that the visible camera lens could be obscured by the window bezel or rear panel cover if care is not taken in setting up the camera position and angle to the window.

5.3 Potential Future Work

There are manufacturing and procedural hurdles to overcome, as noted above. The Navy is currently revising standards to incorporate IR windows into 4160V cabinet design. Manufacturing details will be worked out between the cabinet manufacturers, the shipyards, and the Navy. This project has determined that IR windows are a viable method to provide a safe inspection of these panels where there is no current method to do so.

Thermographic inspection through IR windows also provides a simpler procedure in some respects than the current inspection of 450V panels through open covers. Using windows, it is no longer necessary to secure the area, shut off the power to open the cabinet, don PPE and repower the cabinet for the inspection and then reverse the process to get back into service. However, in other respects, using the windows and the requirement for dust boots in the higher voltage panels complicate a thermographic inspection. The geometry of the components inside the cabinet will make it difficult to obtain line of sight viewing of all areas of interest. The dust boots preclude direct thermal inspection of the connections. The window field of view is sufficient to permit all inspections, but it does put some restrictions on the location and angle of the camera. Lighting the interior for taking visible images adds additional difficulties. Some ship electrical panels have installed arc flash detection devices utilizing only photodetectors that are sensitive in the visible wavelengths. These systems would need to be deactivated during an inspection and reactivated afterwards. Also, the 4160V panels are going into ships where the space behind the panels is typically very restricted, making it awkward, or quite difficult in some instances to make this inspection.

A long term solution that bypasses these difficulties would be to have some permanently installed automated method of inspection for loose connections that would provide continuous monitoring and would alert the ship operator of actual or impending problems. Some methods were explored at the beginning of this project and were considered not as promising as the IR windows. Additional methods have come to light that have some promise. A new NSRP Electrical Technologies panel project is being proposed to investigate these new methods to determine if they are technically feasible and cost effective. Although other methods will be reviewed, the primary focus will be on Distributed Temperature Sensing (DTS) using fiber optics. This technique determines temperature along an optical fiber. The fiber could be embedded along the cabinet bus bars and be able to read temperature at any of the cabinet connections through a single fiber. This would be done underneath the dust boots and there would be no need for windows or line of sight concerns. There are at least three different technical approaches for doing DTS along a fiber. This project would examine these and any others that might be available. Technical feasibility will be assessed, particularly the temperature and spatial resolution and sensitivity. Cost to implement and cost to operate and maintain will also be considered. The project will examine the tradeoffs, both technical and economic, between the different technologies.

6.0 References

6.1 Other Advisors / Stakeholders

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6.3 Relative Merits of Crystal vs. Polymer IR Window

Transmissivity Bandwidth

The statements are that polymer windows have full transmissivity in the long wave IR band (8-14 μm) and crystal windows roll off in this band.

This is somewhat true, but is irrelevant for the IR thermography inspections. The transmission bandwidths for both window types are not flat, but vary somewhat as the wavelength changes. Polymer windows generally speaking, do maintain the transmission across the long wave band, and the crystal material does have a roll off around 10 μm or so. However, this is accounted for in the transmissivity settings of the IR cameras. The camera setting compensates for the losses through the window no matter which type of window.

In our laboratory tests, although the transmissivity settings indicated that the polymer windows were letting more IR radiation through than the crystal, there was no difficulty at all in getting accurate measurements with either window provided the transmissivity settings were correct in the camera. For the comparison test used in shipboard inspection, this is even less relevant, as it is the difference in measurements and not the absolute measurement that is important.

Window Construction as it Affects Viewing

The crystal windows are clear and there are no obstructions. The polymer windows all have a reinforcing grid on one or both sides. Some of the polymer windows are translucent to visible light and therefore preclude doing visible imaging through the same window, although clear polymer is available. The reinforcing grid has a noticeable, but small effect on the infrared thermal measurements (a couple of % difference at most). The reinforcing grid does have a significant effect on visible imaging. It is possible to image around the grid, but difficult to get the area of interest unobstructed.

The grid has less of an effect if the camera lens is placed directly against the window as recommended by the polymer window manufacturers. Polymer windows can also be obtained in rectangular shapes larger than the crystal windows. This increases the chance that the camera can be placed directly against the window directly in front of the area of interest inside the cabinet. However, the geometry of some cabinets requires that connections mounted behind other structures be imaged from an angle. This prevents the camera lens from being placed directly on the window, and the grid is therefore still an issue even if the window itself is large and rectangular. Given that the crystal window FOV is so large, the larger rectangular polymer windows with their accompanying grid do not provide much of an advantage.

While it is certainly possible to get both IR and visible images through the polymer window reinforcing grid, it complicates the inspection and certainly causes issues that are not present with the clear crystal windows.

Both windows have a problem with reflected glare when visible imaging with the camera's built in lamp. The problem is slightly worse with the polymer window as the grid also reflects light and causes the camera's autofocus to focus on the grid rather than what is beyond it.

Durability

Both windows meet either the IEC 62271-200 standard or the ANSI/IEE C37.20.7 standard for withstanding arc flash.

The manufacturer of the polymer window (IRISS) claim that the polymer window passes the IEEE C37.20.2 standard for impact resistance and that crystal windows do not. We have not found any reference with crystal windows evaluated against this standard. However, this standard is an impact test, involving dropping steel balls on the window from a height and its relevance to a panel installation is a matter for the Navy to determine.

The polymer window material tends to be very thin. The sample we had was 0.0039" thick and was easily punctured by a pencil point. However, the grid would restrict any puncture to the size of the grid openings. Again, the relevance of this information needs to be determined by the Navy.

The crystal windows meet the IEC 60068 standard for vibration but no specs are given for polymer windows on this. NSWC Philadelphia successfully tested two crystal windows against MIL-STD-167-1A for vibration and against MIL-S-901D for shock. Copies of these reports are available through NSWC Philadelphia. Thus, crystal windows have passed Navy and industry tests for vibration and shock, but we have not found corresponding tests for polymer windows, other than the aforementioned impact test.

Degradation Over Time

According to the polymer window manufacturer, the main disadvantage of crystal windows is that they absorb moisture over time, which degrades their transmissivity and makes them unfit for marine use.

The crystal window manufacturers counter with the following:

- Fluke says their windows meet IEC 60068-2-3 for humidity, are certified for Marine use and have a protective coating that is durable (not scratched by incidental contact). Fluke also says that polymer windows will degrade and become brittle over time due to UV exposure, but we have no data on this one way or the other.
- FLIR says theirs are designed for high humidity, meet the IEC 60068-2-3 humidity spec, have a lifetime warranty (minimum 10 years), and have a negligible return rate after 15 years in service, including those used outdoors. FLIR also says in their internal tests (proprietary to FLIR – copy was not available), the crystal window only showed degradation of 1-2% when immersed in water for a full year. In a marine environment aboard ship, degradation would only be about a % over 2-3 years. This is easily compensated by the transmissivity settings of the camera (even in lab tests, the transmissivity setting varied a % or two over the duration of the testing).

- FLIR says that they call attention to the degradation in their literature, only because these windows are sometimes used in laboratory settings where the absolute accuracy is important. For relative temperature measurements as is used in ship board inspection, this would not affect the measurements.

In summary, the degradation of crystal windows is slight, occurs under extreme conditions over many years, and does not affect the relative temperature measurements used in ship panel inspection.

Cost

It is hard to get a direct comparison of cost for the windows, as windows with identical features except for window material were hard to come by. In the nearest comparison, in single unit quantities, the crystal window was not quite 4% more expensive than the polymer. However, the more significant factor seems to be the housing. A stainless steel housed crystal window was (single quantity) 18% more expensive than the aluminum housed polymer window. There was no equivalent stainless steel polymer window available for testing. For single units, retail costs are roughly about $100 per inch of window diameter (e.g. 4” window is ~ $400, etc.).

Conclusion

Either type of window could be made to work, but advantage goes to the crystal window. It has better field of view, much better ability to take visible images and has already passed Navy vibration and shock tests. The complaints about the crystal windows (bandwidth roll-off and degradation over time due to moisture) do not affect the testing and durability of the crystal windows.

6.4 IR Windows and Cameras Reviewed

IR Window Comparison										
No.		FLIR IRW Series	FLIR IRW S*	Exiscan XIR-A-4-H-X	Exiscan XIR-A-3-H-X	Exiscan XIR-S-4-H-X	Fluke CLirVu	Fluke CLKT	IRISS VPFC	IRISS VPT
1	Permanently attached cover	Y	Y	Y	Y	Y	Y	N	Y	Y
2	Single hole installation	Y	Y	No, 8 bolts	No, 8 bolts	No, 8 bolts	Y	3 self tap screws	??	??
3	standard hole punch install	Y	Y	Saw or punch	Saw or punch	Saw or punch	Y	Y	??	??
4	Solid metal cover	Y	Y	Y	Y	Y	Probably	Probably	Y	Y
5	No tools to open window	single thumbscrew	single thumbscrew	4 hex head captive screws	4 hex head captive screws	4 hex head captive screws	1/4 turn hand turn captive	Hex head screw	Phillips screw	Phillips screw
6	Broadband (vis and thermal)	Y	Y	No, separate window for vis	No, separate window for vis	No, separate window for vis	Y	Y	Y	Y
7	No obstructions, including reinforcing screens	Y	Y	Diamond reinforcing screen	Diamond reinforcing screen	Diamond reinforcing screen	Y	Y	Y	Hex reinforcing screen
8	Rated to 250 °C	260 °C	260 °C	150 °C	150 °C	150 °C	232 °C & 260 °C intermittent	250 °C	200 °C	200 °C
9	Stainless Steel housing	Anodized Alum.	316 Stainless Stl	anodized Alum, pwdr coat	anodized Alum, pwdr coat	Stainless	"high strength alloys"	Aluminum	Nylon	Nylon, SS cover
10	Pull out strength 3600 lbs.	2" 1450 lb. 3" 3650 lb. 4" 3700 lb.	2" 1450 lb. 3" 3650 lb. 4" 3700 lb.	No Spec	No Spec	No Spec	No spec	1388 lb.	No Spec	No Spec
11	Rated low, med, high voltage	Y	Y	Y	Y	Y	Y	Y	??	??
12	Meet UL 50V	Y	Y	Y	Y	Y	Y	?	Y	Y
13	Meet UL50 Environ. Type 4/12	4/12	4/12	4	4	4	4/12	3/12	4	4
14	Meet KEMA (IEC 62271-200) Arc flash 5kV, 63 kA 30 cycles 60 Hz.	5 kV, 63 kA 30 cycles 60 Hz	5 kV, 63 kA 30 cycles 60 Hz	ANSI/IEEE C37 20.7	ANSI/IEEE C37 20.7	ANSI/IEEE C37 20.7	63 kA 30 cycles 60 Hz, meets C37 20.7	C37.20.7 50 kA for 30 cycles 60 Hz	??	C37.20.7 63 kA, 15 kV for 30 cycles 60 Hz
15	Meet TUV (IEC 60529) IP67	IP 67	IP 67	IP65	IP65	IP65	IP67	IP65	IP65	IP65
16	Meet TUV (IEC 60068) 100 m/s^2 vibration	100 m/s^2	100 m/s^2	No Spec vibration "unaffected"	No Spec vibration "unaffected"	No Spec vibration "unaffected"	IEC 60068-2-6	IEC 60068-2-6	??	??
17	Meet TUV (IEC ^0068-2-3) 15 day extreme humidity	Y	Y	Humidity & moisture "unaffected"	Humidity & moisture "unaffected"	Humidity & moisture "unaffected"	IEC 60068-2-3	IEC 60068-2-3	??	??
18	Optic Material	Calcium Fluoride	Calcium Fluoride	Polymer	Polymer	Polymer	Crystal	Crystal	Calcium Fluoride	Polymer
19	Two Inch Diameter	IRW-2C	IRW-2S				CV200	FLK-050-CLKT	VPFC-50	VPT-50
20	2" Optic diameter	50 mm (1.97")	50 mm (1.97")				50 mm (1.97")	50 mm (1.97")	51 mm (2.0")	51 mm (2.0")
21	2" Viewing aperture diameter	45 mm (1.77")	45 mm (1.77")				42.93 mm (1.69")	43 mm (1.7")	??	??
22	2" Window Cost	$195	$249				$250 link D	$200 link G	$196 Link J	$172 Link K
23	Three Inch Diameter	IRW-3C	IRW-3S				CV300	FLK-075-CLKT	VPFC-75	VPT-75
24	3" Optic diameter	75 mm (2.95")	75 mm (2.95")				75 mm (2.95")	75 mm (2.95")	76 mm (3.0")	76 mm (3.0")
25	3" Viewing aperture diameter	69 mm (2.71")	69 mm (2.71")		3" x 3" square		67.95 mm (2.68")	68 mm (2.7")	??	??
26	3" Window Cost	$295	$349		$325		$350 link E	$300 link H	$264 Link J	$260 Link K
27	Four Inch Diameter	IRW-4C	IRW-4S				CV400	FLK-100-CLKT	VPFC-100	VPT-100
28	4" Optic diameter	95 mm (3.74")	95 mm (3.74")				95 mm (3.74")	95 mm (3.74")	102 mm (4.0")	102 mm (4.0")
29	4" Viewing aperture diameter	89 mm (3.5")	89 mm (3.5")	4" x 4" square		4" x 4" square	87.63mm (3.45")	89 mm (3.5")	??	??
30	4" Window Cost	$395	$449	$365		$999	$500 link F	$360 link I	$408 Link J	$380 Link K
	Link	A	A	B	B	B	C	C		

IR Window Links	
A	http://www.flir.com/instruments/display/?id=50386
B	www.exiscan.com
C	http://en-us.fluke.com/products/ir-windows/
D	http://www.coleparmer.com/Product/Fluke_CV_Series_ClirVu_2_Infrared_Inspection_Window/EW-39750-61
E	http://www.coleparmer.com/Product/Fluke_CV_Series_ClirVu_3_Infrared_Inspection_Window/EW-39750-63
F	http://www.newark.com/fluke/fluke-cv400/infrared-inspection-window-4-inch/dp/99W5464?ost=FLUKE-CV400&CMP=AFF-CJ-4150139-Newark+Redirect+Link&source=CJ
G	http://www.alliedelec.com/fluke-flk-050-clkt/70145915/?psrid=77434851
H	http://www.newark.com/fluke/flk-075-clkt/infrared-ir-window-indoor-outdoor/dp/10R2303?in_merch=Popular%20Products&CMP=AFF-CJ-4150139-Newark+Redirect+Link&source=CJ
I	http://www.transcat.com/fluke-hwk-100-clkt-flk-100-clkt
J	http://www.ie-central.com/shop/infrared-windows/iriss-vpfc/
K	http://www.infraredcamerawarehouse.com/search.php?search_query=VPT-75&x=0&y=0

IR Camera Comparison					
Feature	FLIR E-50	FLIR EX320	FLIR E-60	Fluke TI32	FLIR T440
Source	Ingalls	Supships	Supships	Ingalls	Zabita
Link	A	B	C	D	E
Use	Ingalls uses in R&D	Used by Supships	Replaces EX320	Ingalls Operations Dept. (Production)	Navy Fleet use
Temp range	-20° C to +650 °C	-20° C to 250 °C and 0° C to +500 °C	-20° C to +650 °C	-20° C to +600 °C	-20° C to +1200 °C
Temp accuracy	greater of +/- 2 °C or 2%	greater of +/- 2 °C or 2%	greater of +/- 2 °C or 2%	greater of +/- 2 °C or 2%	greater of +/- 2 °C or 2%
onscreen emissivity correction				Yes	
onscreen reflected background compensation	?	Yes	?	Yes	?
onscreen transmission correction				Yes	
IR Window Correction (same as transmission correction?)					Yes
Capture frequency	60 Hz		60 Hz	9 Hz (60 Hz depending on model)	60 Hz
Detector	240x180 uncooled microbolometer	320x240 uncooled microbolometer	320x240 uncooled microbolometer	320x240 uncooled microbolometer	320 x240
NETD	<0.05 °C	<0.08 °C	<0.05 °C	< 0.045 °C	< 0.04 °C
IR band		7.5 to 13 µm		7.5 to 14 µm	
Minimum focus distance				46 cm (18 in.)	40 cm (1.31 ft.)
Standard lens FOV	25°	25° x 19°	25°	23° x 17°	25° x 19°
Std Lens IFOV				1.25 mrad	
Std Lens Min focus distance				15 cm (6 in.)	
Wide angle lens FOV	45° (optional)	45° x 36° (optional)	45° (optional)	46° x 34° (optional)	45°(optional), 90°(optional)
Wide angle IFOV				2.5 mrad	
Wide angle min focus		.2 m		7.5 cm (6 in.)	
Telephoto FOV	15°	15° x 11° (optional)	15°	11.5° x 8.7° (optional)	6° (optional), 15° (optional)
Telephoto IFOV				.63 mrad	
Telephoto min focus		.5 m		45 cm (6 in.)	
Digital Zoom	4x continuous	1x, 2x, 4x	4x continuous		2x, 4x, 8x
Laser targeting spot		Yes	Yes		Yes
Level and span				auto and manual scaling	
Minimum span				5 °C (auto) 2.5°C (man)	
Built in Visual Camera	3.1 MP	No?	3.1 MP	Yes	3.1 MP
Built in Illuminator	Yes		Yes	Yes	LED
Automatic fuse vis and IR	No		No	Yes	
Picture in Picture	Scalable		Scalable	3 levels	Scalable
Full screen IR				3 levels	
Adjustments on captured image before it's stored				Yes	
Screen annotation	Yes		Yes		Yes
Voice annotation	Yes		Yes	Yes	
Storage file format	SD card		SD card	SD card (2 GB)	SD card
Export file format	jpg (radiometric) MPEG4 non-radiometric	jpg	jpg (radiometric) MPEG4 non-radiometric	.bmp, .jpg. .is2 (radiometric)	Jpeg radiometric, MPEG4 non-radiometric
Store metadata		Yes			
Display	3.5" diagonal LCD 320 x 240	2.5" diagonal LCD 320 x 240	3.5" diagonal LCD 320 x 240	9.1 cm (3.7") diagonal 640 x 480 LCD	3.5" diagonal
Touchscreen	Yes		Yes		Yes
Software included	FLIR Tools	ThermaCAM QuickView	FLIR Tools	SmartView analysis and reporting software	UltraMax
Battery Life	4 hours	2 hours	4 hours	4+ hours	4+ hours

IR Camera Links	
A	http://www.flir.com/instruments/display/?id=56911
B	N/A
C	http://www.flir.com/instruments/display/?id=56911
D	http://en-us.fluke.com/products/infrared-cameras/fluke-ti32.html#techspecs
E	http://www.flir.com/instruments/display/?id=62960

Safer Inspection of Medium Voltage Electrical Panels on Navy Ships

The National Shipbuilding Research Program

2015 Electrical Technologies Panel Project

Laboratory Test Report

October 23, 2015

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Executive Summary

The objective of this testing was to evaluate thermal imaging through IR windows under laboratory conditions and to compare the two main types of available windows: crystal and polymer. It was not the intent to determine if IR windows work for infrared thermography. They are sold as a commercial product for that purpose. Rather it was to setup some baseline measurements to determine how the windows affect the temperature measurements and to ascertain how their performance might impact a shipboard thermography inspection.

Most of the tests were conducted using a blackbody radiation source as a repeatable heated target. This helped establish the baseline performance. The last few tests used representative cables and bus bar heated to different temperatures to simulate a panel inspection with a wiring fault. Two thermal cameras were used and four IR windows were evaluated. After initial testing, this selection was reduced to one camera and two windows, one crystal and one polymer. Multiple tests were run, as described in this report.

The most significant things learned were:

- Reasonably accurate temperature measurements can be made through IR windows provided attention is paid to emissivity and transmissivity settings in the camera. Some small variation in transmissivity settings from day to day would need to be accounted for when developing procedures for practical tests.

- Variations in target (cable lugs) surface geometry and condition make the measurements very sensitive to the location of the measurement point in the image. The Navy accounts for this by using a common emissivity setting for all tests and noting that it is temperature difference between adjacent phases in the connection that is important rather than the absolute temperatures. These issues can be minimized by developing uniform techniques and procedures to provide a useful comparison test.

- The windows provide an extremely wide horizontal and vertical field of view allowing visual access to most of a cabinet through a single window, limited only by internal obstructions. This will allow more flexibility in the placement of the window(s) in the panel and the use of fewer or smaller windows.

- The polymer windows all have a reinforcement grid behind the viewing surface. This is evident in the imaging but does not affect the thermal measurements in a significant way. However, it does reduce the field of view compared to the clear crystal window and it affects visible images taken through the grid. Some polymer windows are translucent, which precludes taking visible images at all. Crystal windows are recommended for this reason.

- The rubber boot material that covers the connections in recent panels does affect the measurements between connections at different temperatures. However sufficient differences can be seen in the temperature of the boot over the connection and in the cables as they exit the boot to indicate that one connection is significantly hotter than the other.

- Reflected glare off both windows affects visible images taken with the camera's own illumination source. As the intent of the window is to allow viewing with the panel cover closed, some other method of illuminating the interior will be needed.

Introduction

The objective of these tests was to examine the performance of IR windows of different types and manufacturers in IR thermography under laboratory conditions and to determine possible impacts of that performance in shipboard panel inspection. Four different IR windows and two IR cameras were used in the testing. In general, the tests followed the test plan document, Final Test Plan Notes (9.18.15)(v.2) previously distributed. Some modifications were made to the plan as the testing progressed. The testing took place between September 18, 2015 and October 7, 2015 at the Penn State University Electro-Optics Center, Freeport, PA. This report describes the testing and the results.

1 Test Setup

While the intent of the testing was to evaluate IR windows, different cameras were also included. It was not anticipated that a different camera would return significantly different results. However, certain camera features may have a different interaction with an IR Window between one camera and another. This section also includes the test setup that was common to all tests. Variations in setup are described under the sections for each test.

1.1 Cameras

It was intended to use three cameras for the testing. One camera, a FLIR E60 from SUPSHIPS Gulf Coast was unavailable during the testing period. Instead, SUPSHIPS sent their backup camera, an older model FLIR EX320. This camera was examined in preliminary testing and it was decided not to use it, as its feature set was not as advanced as the other two cameras and it did not have a built in visible camera. The FLIR T440 and Fluke TI32 were used instead.

1.1.1 FLIR T440

The FLIR model T440 was obtained on loan from FLIR. It is a recent model of the FLIR 400 series thermal cameras currently used by the Navy for thermographic inspections. It has both visible and IR cameras, a variety of settings to compensate for the testing conditions, including a setting for the transmissivity of the IR window, and the ability to store the images. The most common measurement tools for the FLIR camera are a spot and a box. The spot is a crosshair that can be moved to any location on the image. The display then indicates the temperature at the crosshair. The box can be moved and resized, and indicates an area in the image. The maximum temperature in the box is displayed.

1.1.2 Fluke TI32

The Fluke model TI32 was borrowed from Huntington Ingalls shipyard. It is also a recent model thermal camera. It has both visible and IR cameras, and a variety of settings (although not always the same settings as the FLIR camera), and the ability to store images. The Fluke camera has a movable, resizable box, but no spot. The display indicates the minimum, maximum and average temperatures in the box.

1.2 Windows

Four different windows were purchased for evaluation. Three of them are round with 4 inch diameter. The fourth is square, 4 inches on a side. The actual viewing area is slightly smaller than the 4 inch nominal size. This is the largest commonly available window size. The four chosen represent two of the crystal type window and two of the polymer type. Crystal windows also are transparent to visible light, but suffer some transmission dropoff in the higher IR wavelengths. Polymer windows are mostly translucent to visible light and have a little higher bandwidth. Both polymer windows contain a metal backing grid that gives the window additional strength but must be taken into account when imaging. All windows have a metal cover that protects the windows under normal operation, then is hinged or slides out of the way for imaging. All the covers were removed for the laboratory tests.

1.2.1 FLIR IRW-4S

This is a crystal (Calcium Fluoride) window in a stainless steel housing. The actual viewing aperture is 89mm (3.5") once the bezel is accounted for. The specifications for this window are the closest to the preliminary specification for the LHA-8 panel inspections.

1.2.2 Fluke CLirVu CV400

This is also a crystal window, although Fluke does not specify the material. The actual viewing aperture is 87.63 mm (3.45"),

1.2.3 Exiscan XIR-A-4-H-X

This is a polymer window, with a square viewing aperture of 4" on a side. The window is translucent to visible light, presenting a milky appearance so lights and darks can be seen through it, but no image. If a visible image is required, an adjacent clear window would be required in the panel cover. The metal grid on the back is of a diamond pattern, with fairly large openings (each edge of the diamonds is about 0.5").

1.2.4 IRISS VPT-100

This is a polymer window, although it is transparent in visible light. It has a hexagonal reinforcing screen with fairly small openings (each edge of the hexagon is about 0.25").

1.3 Equipment and Conditions

All of the laboratory tests were staged on a 4 foot by 8 foot optical table with mounting holes on a 1 inch grid pattern throughout. This allowed a repeatable setup for testing the different cameras and windows in the same geometry. The FLIR camera has a standard ¼-20 threaded hole under the lens for tripod mounting. A rod was threaded into this hole and secured in a stand screwed to the optical table to maintain the camera in a desired position. The Fluke camera does not have a threaded hole. Instead, a vertical rod with a horizontal bar across the top was secured into the same stand and the Fluke camera was rested against this bar.

Two more vertical rods were secured to the table approximately 5 inches apart and just in front of the camera lens. Each window was then secured to these rods with one or two spring clamps. This allowed a repeatable position for the windows, but also allowed them to be easily changed throughout the different tests. The windows were approximately 1 inch in front of the camera lens. Figure 1 shows the FLIR T440 camera mounted on the vertical post with the FLIR IRW-4S window clamped on the fixture in front of the camera lens.

Figure 1 Camera and Window Holding Fixtures

The heat source target for the initial tests was a model SR-80 blackbody source from CI Systems. The instrument head radiates heat as a near perfect blackbody (with emissivity of 0.97). The head has a square surface of 7” by 7” and can be set to any temperature between 20°C and 87°C via a controller. The controller also reports the ambient temperature at the blackbody head. This was used as a more reliable and repeatable heat source than hot plates or heated liquids in cups. The high emissivity also allowed a repeatable camera setting for tests conducted on different days. The upper temperature allowed testing at all but the highest expected ranges for ship panel thermography. Figure 2 shows the blackbody source head at the upper right and controller at the lower left.

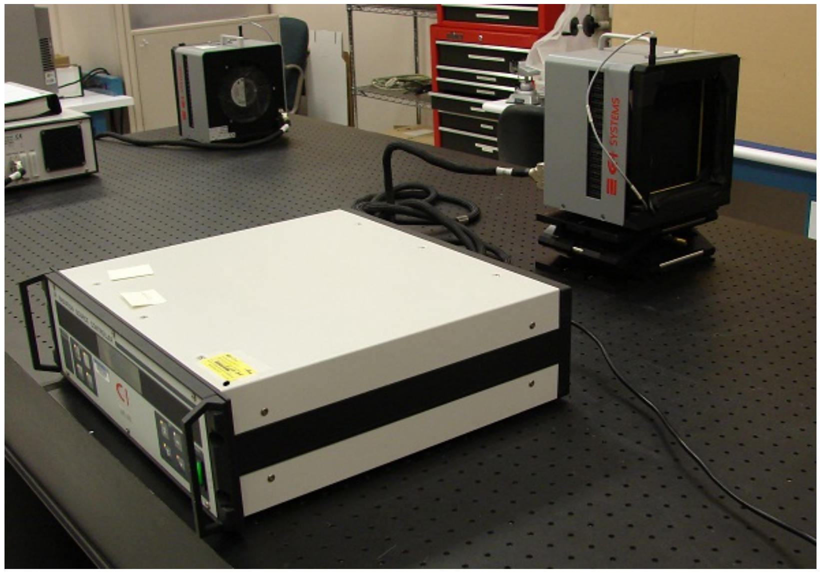

Figure 2 Blackbody Source and Controller

The head has been placed on a platform that permitted the head to be raised to a level at which the center of the head was even with the camera lens. Two blackbody source instruments were checked in preliminary testing. Both yielded the same results. This one was chosen since its maximum temperature was somewhat higher than the other. Some other targets were used in later tests and they will be described in those sections. Unless otherwise noted, the target face was placed 18 inches away from the window position (19” from the camera), which is considered to be representative of the distance in an actual panel inspection.

2 Test A – Camera Evaluation for Accuracy

This test evaluated the two cameras with no windows against the same blackbody source, to set a baseline for the camera thermal measurements.

2.1 Test A Setup

With no windows, each camera was set up 19” from the blackbody source surface. The blackbody was set for temperatures of 35°C, 55°C and 75°C for each camera. The cameras were both set for an emissivity of 0.97 to match the blackbody. Both cameras allow the ambient temperature to be entered as a background temperature. Ambient temperature was read from the blackbody controller. The FLIR camera also allows relative humidity and distance to be entered. These factors are meant mostly to compensate for environmental conditions outside and are relatively insignificant for these laboratory tests, but they were recorded and entered into the cameras anyway.

Both cameras have a setting for Transmissivity when using a window. For this test and all tests without windows, the transmissivity (Tr) was set to 100%. The FLIR camera also has a setting to turn the transmissivity off, but the reading is no different than having it turned on and set to 100%. For all future tests with no window, the FLIR camera was set with transmissivity on and set to 100%. The measurement boxes for both cameras were at the default sizes and centered on the image. The FLIR spot crosshair was in the center of the box. For all measurements in all tests, both camera displays were set to show a temperature scale in colors with the hotter temperatures in brighter colors (red to orange to yellow) and the colder temperatures in darker colors (blue to purple to black). The color depiction was set to auto scale, so the difference between the hottest and coldest spots in the image set the scale. Therefore, colors in one thermal image shown in this report should not be compared to colors in another image as the scale may be different. Refer to the temperature measurements in the image or in the tables presented in the report. The two cameras also present the colors slightly differently.

2.2 Test A Data

Table 1 shows the camera readings for the three temperatures.

Camera Measurement	Blackbody Setting		
	35°C	55°C	75°C
FLIR T440 Spot	35.4	55.9	75.9
FLIR T440 Box Maximum	35.7	56.3	76.2
Fluke TI32 Average	36.9	56.4	75.9
Fluke TI32 Minimum	36.7	56.2	75.6
Fluke TI32 Maximum	37.2	56.6	76.2

Table 1 Camera Compare, No Windows

Looking at the FLIR Spot measurement, it differs from the blackbody setting by 0.4, 0.9 and 0.9°C. The Fluke Average measurement differs by 1.9, 1.4 and .9°C.

The box maximum readings differ by 0.7, 1.3 and 1.2°C for the FLIR and 2.2, 1.6 and 1.2°C for the Fluke.

Figure 3 shows the image captured from the FLIR camera at the 55°C setting.

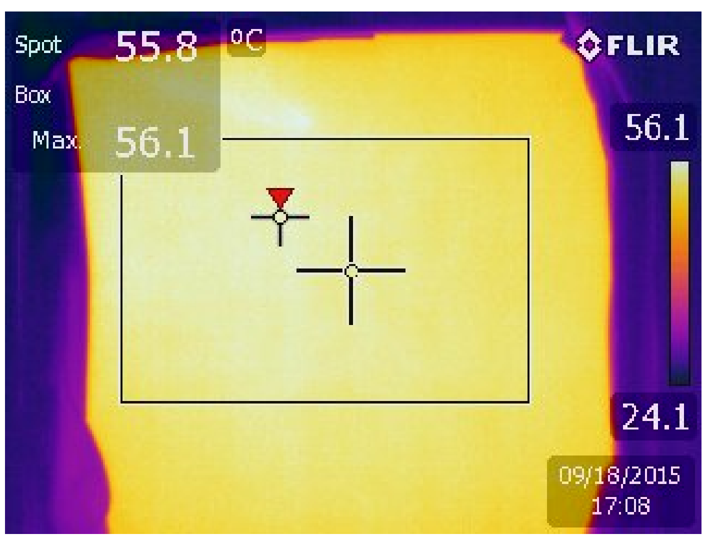

Figure 3 FLIR T440 Camera Captured IR Image

The yellow is the image from the black body source and is uniform across nearly its entire surface. The borders are somewhat irregular as they were masked off with black tape and the tape was not exactly straight. As this was outside the area of interest, it was ignored. The colder temperatures on the border of the picture are the frame of the blackbody source, which is essentially at ambient temperature.

It may be noted that the spot temperature in the image differs slightly from that recorded in the table. Even with everything held fixed, the temperature readouts on both cameras would vary up to half a degree or more. The temperature was noted at a different time than when the image was recorded. These variations are common to all of the camera measurements.

Figure 4 shows the corresponding image from the Fluke TI32 camera at 55°C.

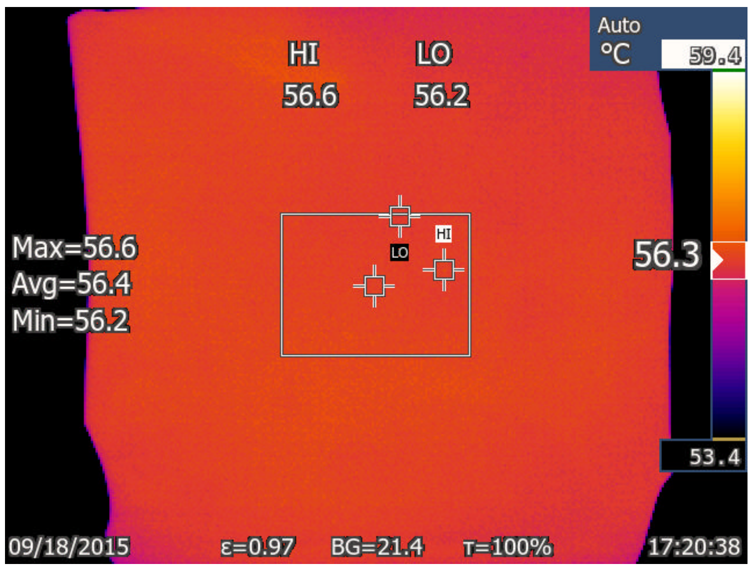

Figure 4 Fluke TI32 Camera Captured IR Image

2.3 Test A Summary

Just by the numbers, the FLIR camera looks slightly better at the lower temperatures and the cameras are essentially the same at the higher temperature. However, given that there are slight variations in readings even with the camera sitting stationary, these differences were judged not to be significant and the cameras performed essentially the same with no windows.

3 Test B – Window Evaluation for Transmissivity

This test evaluated all four windows with both cameras to see the effects of the windows on the temperature measurements and the ability of the cameras to compensate using the transmissivity setting in the camera.

3.1 Test B Setup

The same physical setup was used as in Test A. All four windows were tested with the FLIR camera at a target setting of 35°C. The camera was set for Tr=100% and no window was in place, to get a baseline reading from the blackbody. The window was then added but the transmissivity was left at 100% to see the uncompensated effect of the window. The transmissivity was then adjusted until the temperature reading matched the reading with no window. In some cases, the transmissivity was also further adjusted so the temperature reading matched the black body source setting. For all tests, emissivity was set to 0.97.

The same test sequence was repeated for the remaining three windows, starting with no window and Tr=100%. This sequence of tests was repeated with the other camera also at 35°C target temperature. The entire test sequence was repeated with the target set to 55°C.

3.2 Test B Data

Table 2 shows the results for the FLIR T440 camera and all four windows with the blackbody set to 35°C.

Window	Tr (%)	Spot (°C)	Notes
No Window	100	35.9	
FLIR	100	26.8	
FLIR	38	35.7	Tr set to match no window reading
No Window	100	35.9	
Fluke	100	26.8	
Fluke	38	35.8	
No Window	100	35.9	
Exiscan	100	31.1	Placed camera to get spot between grid lines
Exiscan	67	35.9	Tr matched no window
No Window	100	35.9	
IRISS	100	29.2	Placed camera to get spot between grid lines
IRISS	55	35.9	Tr matched no window
IRISS	55	37.3	Spot placed on grid node

Table 2 FLIR Camera With Four Windows, 35 deg C

Table 3 shows the results with the Fluke TI32 camera and all four windows with the blackbody set to 35°C.

Window	Tr (%)	Avg (°C)	Notes
No Window	100	38.3	
FLIR	100	29.6	
FLIR	48	38.3	Tr set to match no window reading
No Window	100	37.3	
Fluke	100	29.4	
Fluke	49	37.3	Tr matched no window
No Window	100	37.3	
Exiscan	100	33.1	Hard to get center of box between grid lines
Exiscan	74	37.3	Tr matched no window
No Window	100	37.4	
IRISS	100	30.7	Placed camera to get center of box between grid lines
IRISS	60	37.5	Tr matched no window

Table 3 Fluke Camera with Four Windows, 35 deg C

Table 4 shows the results for the FLIR T440 camera and all four windows with the blackbody set to 55°C.

Window	Tr (%)	Spot (°C)	Notes
No Window	100	55.5	
FLIR	100	33.9	
FLIR	32	55.5	Tr set to match no window reading
No Window	100	55.8	
Fluke	100	34.3	
Fluke	32	55.5	
No Window	100	55.9	
Exiscan	100	42.6	Placed camera to get spot between grid lines
Exiscan	57	55.6	Tr matched no window
No Window	100	56.0	
IRISS	100	39.2	Placed camera to get spot between grid lines
IRISS	44	55.8	Tr matched no window

Table 4 FLIR Camera with Four Windows, 55 deg. C

Table 5 shows the results with the Fluke TI32 camera and all four windows with the blackbody set to 55°C.

Window	Tr (%)	Avg (°C)	Notes
No Window	100	56.4	
FLIR	100	37.7	
FLIR	45	56.5	Tr set to match no window reading
No Window	100	56.3	
Fluke	100	38.6	
Fluke	45	56.5	Tr matched no window
No Window	100	56.1	
Exiscan	100	46.5	Hard to get center of box between grid lines
Exiscan	71	56.3	Tr matched no window
No Window	100	56.2	
IRISS	100	40.9	Placed camera to get center of box between grid lines
IRISS	53	56.5	Tr matched no window

Table 5 Fluke Camera with Four Windows, 55 deg. C

Without compensation added into the camera for the transmission loss, the reported temperatures are about 10°C lower than the readings without windows at 35°C and about 20°C lower at 55°C.

From all four of these tests, it can be seen that the transmissivity setting is lower for the two crystal windows than for the two polymer windows. This is consistent with the understanding that the crystal window transmission falls off at the higher IR wavelengths.

Though not shown in the tables, in some cases, a change was required to the transmissivity setting to get the temperature to the blackbody setting temperature vs. the temperature recorded with no window. Sometimes this change was a few percent, in other cases it was above ten percent, the higher usually when the no window temperature was higher. However, in a practical test the transmissivity setting would be set to the temperature recorded with no window, so this data was not shown.

The reinforcing grids on the polymer windows caused some difficulty getting consistent readings. Figure 5 shows the thermal image taken through the hexagonal grid on the IRISS window at 35°C.

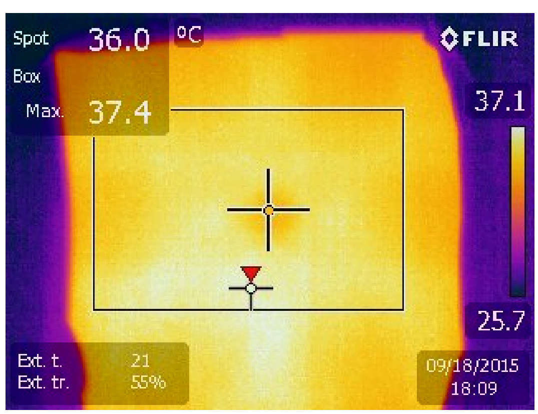

Figure 5 Thermal Image, IRISS Window Grid Lines

In the image, the hexagonal grid pattern is plainly visible. The camera position was moved until the spot measurement was between the grid lines, which indicates somewhat colder than where the grid lines are. The hottest spot, shown by the smaller crosshairs in the box sits where the grid lines cross (at a node) it reads 1.4°C higher than between the grid. While this difference is small, it does illustrate that care must be taken in camera placement when these grid lines are present.

The Exiscan polymer window has a diamond pattern grid with larger openings. Figure 6 shows the Exiscan window at 35°C.

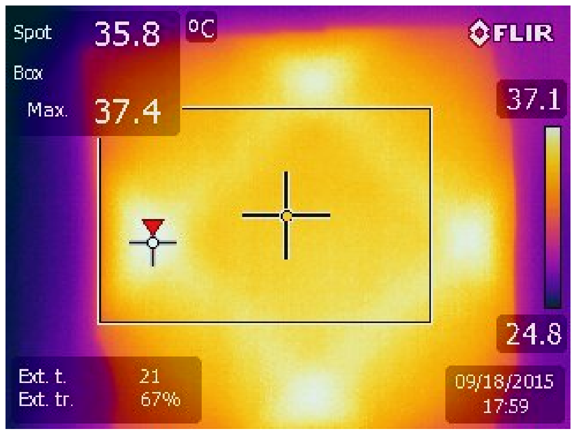

Figure 6 Thermal Image, Exiscan Window Grid Lines

As with the IRISS window, the grid pattern is plainly seen, although the larger opening makes it easier to image through the grid. Also as before, the grid node reads 1.6°C hotter.

3.3 Test B Summary

If the camera is not set to compensate for the presence of the windows, the resulting measurements are too low, by a larger amount at higher temperatures. This makes sense as the camera is only measuring the irradiance from the hot surface and interpreting it as temperature. With less light from the surface reaching the camera through the window, the camera interprets this as a lower temperature. The differences are significant enough that the compensation in the camera must be used for measurements through the window.

The polymer windows have a higher transmissivity setting than the crystal window, which means the polymer transmit more light at these wavelengths, which was expected from the material characteristics. However, accurate readings can be made at the lower transmissivity settings for crystal, so in a practical sense it makes no difference.

The two crystal windows behave virtually identical to each other with both cameras, suggesting that they are the same material (Fluke does not specify which material they use). The two polymer windows differ from each other in terms of transmissivity, which is likely due to the material properties.

The reinforcing grids were evident in the images from both polymer windows, and did make a difference as to the temperature reading, although the difference was small.

The transmissivity settings varied between the cameras for the same window. It is not clear why this would be so, unless the algorithms used to process the imager differ between manufacturer. Transmissivity numbers also vary at the different temperatures. The settings are not that far apart.

The differences in transmissivity settings between cameras and temperature would be taken into account when developing test procedures for practical tests. Given that panel inspection thermography is a comparative test between two measurements, the absolute accuracy is not as significant. Settings will need to be developed that provide reasonably consistent results in comparative testing while erring on the conservative side by reporting temperatures higher than they might actually be.

4 Test C – Camera and Window Downselect

This is not an actual test but a review of the first two tests in order to downselect to one camera and two windows, one crystal and one polymer, for further testing. This was done to reduce redundancy and keep the testing within the scope of the allocated time.

Both cameras performed well, but the FLIR T440 was chosen to continue with the tests. The FLIR T440 was slightly more accurate and slightly more consistent in readings than the Fluke TI32. However, these differences were small. The choice of the FLIR T440 was based more on features. The T440 is the same model series as that used in the Navy presently, the T440 has the spot cursor for measurements and its interface is slightly easier to use. Finally, the T440 can record separate visible digital images and infrared images, whereas the Fluke TI32 can only record a fused image if a digital image is desired.

For the windows, there is no real difference between the FLIR and Fluke crystal windows. The FLIR window was chosen as being most representative of the LHA-8 preliminary specification. In addition, the FLIR has a geometry more conducive to easy use within the test setup.

The two polymer windows were less alike. The IRISS window was chosen for the remaining tests. The main difference is that the Exiscan window has no visible capability. Not only does this preclude taking digital images through the window, it made it very hard to tell if the thermal image was in focus or not, even though the grid spacing was larger than for the IRISS window.

5 Test D – Full Temperature Range

This test used the downselected camera and windows to record the results across a variety of temperatures.

5.1 Test D Setup

Temperature settings for the blackbody source started at 25°C and were increased by 10°C for each test until a maximum of 85°C was reached. A baseline reading with no window and Tr=100% was taken at the start of each new temperature setting. The transmissivity setting was taken from the settings used in Test B. Settings were taken from the closest temperature in Test B to the setting in this test. The test was then repeated with a transmissivity setting that caused the temperature reading to match that with no window

5.2 Test D Data

Table 6 shows the data from the full range test with the FLIR camera and the FLIR and IRISS windows.

Window	BB T (°C)	Tr (%)	Spot (°C)	Notes
No window	25	100	25.7	
FLIR	25	32	28.4	Tr taken from Test B
FLIR	25	63	25.0	Tr matched blackbody setting
IRISS	25	44	28.6	Grid lines not very visible
IRISS	25	81	25.1	Tr matched blackbody
No window	35	100	36.0	
FLIR	35	38	36.2	Tr from Test B
FLIR	35	42	35.0	Tr matched blackbody
IRISS	35	55	35.7	Tr from Test B. Spot placed between grid lines
IRISS	35	54	36.0	Tr matched no window setting
No window	45	100	45.9	
FLIR	45	38	45.0	Tr from Test B
FLIR	45	37	45.9	Matched No Window
IRISS	45	55	43.7	Tr from test B. Spot between grid lines
IRISS	45	51	45.9	Matched No Window
No window	55	100	56.1	
FLIR	55	32	59.8	Tr from Test B
FLIR	55	36	56.1	Matched No Window
IRISS	55	44	57.7	New camera battery. Tr from Test B
IRISS	55	47	55.5	Matched No Window
No window	65	100	65.9	
FLIR	65	32	70.5	Tr from Test B
FLIR	65	36	66.0	Matched No Window
IRISS	65	44	69.9	Tr from Test B. Spot between grid lines
IRISS	65	48	65.9	Matched No Window
No window	75	100	75.9	
FLIR	75	32	81.6	Tr from Test B
FLIR	75	36	75.9	Matched No Window
IRISS	75	44	79.4	Tr from Test B. Spot between grid lines
IRISS	75	48	75.9	Matched No Window
No window	85	100	85.9	
FLIR	85	32	91.9	Tr from Test B
FLIR	85	36	85.9	Matched No Window
IRISS	85	44	88.0	Tr from Test B. Spot between grid lines
IRISS	85	47	85.6	Matched No Window

Table 6 Full Range Temperature Readings, FLIR and Fluke Windows

5.3 Test D Summary

Accurate readings could be made with both windows over the full range of testing temperatures provided the transmissivity was set appropriately. With the transmissivity setting from a previous test (on another day), the readings tended to be high, particularly at the higher temperatures. However if the transmissivity is set so that the reading matches that for the no window condition, the resulting transmissivity is pretty consistent across the range. The difference in transmissivity between the previous setting and matching the No Window case was typically four percent or less. The one exception was at the 25°C setting where a large difference was required in the transmissivity setting to get the temperatures close. A possible cause is that the blackbody source is not as reliable when the temperature is set close to ambient.

As noted regarding the window testing, the variations in transmissivity settings would be taken into account when setting up a practical test.

6 Test E – Horizontal and Vertical Field of View

This test was to determine how far off angle a target could be viewed through a single window. This will help determine options for window placement in panel covers. Both horizontal (side to side) field of view (FOV) and vertical (up and down) field of view was measured for two windows. The camera lens itself has a certain field of view, which was measured. Other lenses, such as wide angle, or telephoto are available, but the camera used in the test had the standard lens. This test also moved the camera and changed its angle to be able to see an off angle target further away than could be seen without moving the camera.

6.1 Test E Setup

The entire face of the blackbody source was not used for this test. For a more realistic target, an aluminum plate was prepared that would cover the blackbody face. This plate had a cutout the same size and shape of one of the connecting lugs from a typical panel cable. It was then placed on the front of the blackbody source. Figure 7 shows a visible light image of the plate in place.

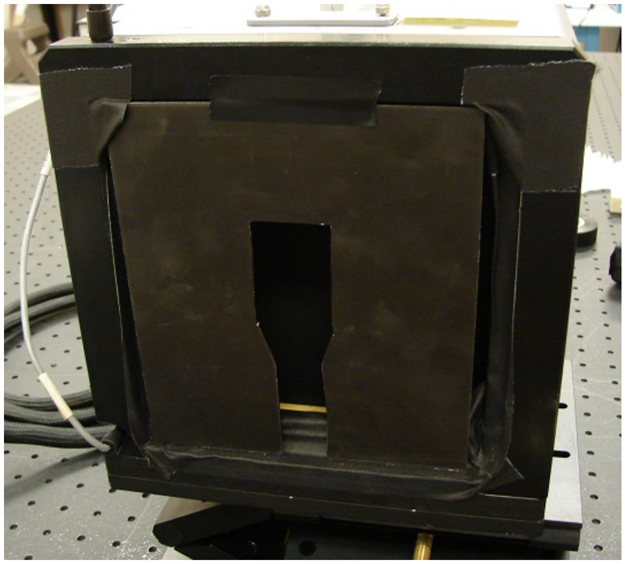

Figure 7 Blackbody Source with Target Mask

The rear of the plate was polished shiny to reflect radiation and the front painted black to emit radiation. The result was that the plate itself remained close to ambient temperature while the lug shaped hole permitted the set temperature of the blackbody source to be visible. Figure 8 shows a thermal image of the target.

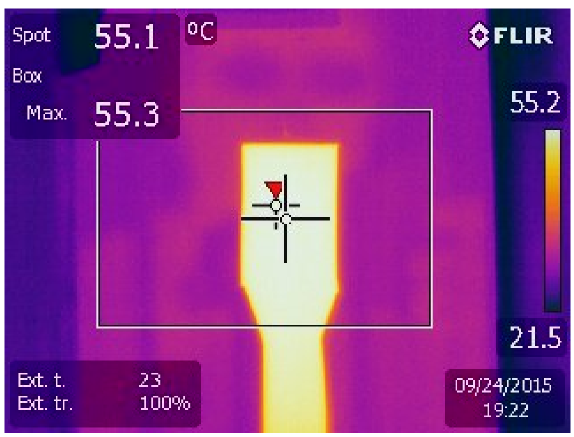

Figure 8 Blackbody Mask Simulating Cable Lug

The mask itself is not perfect, showing a somewhat higher temperature than the edges of the blackbody source, and some reflection is visible on its surface. However, the place of interest within the box and at the spot crosshair shows a correct temperature.

This target was set directly across from the camera setup at a distance of 18 inches from the window surface with the camera lens approximately 1 inch behind the window. The camera was held fixed and the target was moved initially to the left (in the camera view) in small increments until the target was no longer in frame. At each new position, a measurement was recorded and an image taken. This measured the horizontal field of view of the lens. Once this point was reached, the target was moved further to the left in increments of 2 inches at a time, with temperature recorded and images taken at each increment. The camera was moved and its angle changed to get the target more toward the center of the image. In other words, the camera was aimed through the window to get the best view of a target not directly behind, but off to the left of the window.

The blackbody source has a limited field of view itself, so when it moved further to the left, the source was itself angled on its platform to present more of a normal view to the camera lens. However, the center of the target was kept at the recorded horizontal distance. The target was moved to the left until the image being seen was affected by the angle through the window and the window frame itself. The target was then returned to the center and the camera fixed looking straight ahead again, while the test was repeated to the right. After noting the camera lens FOV in the right direction, the remaining distances were only spot checked, rather than run the entire sequence of 2 inch increments.

This horizontal FOV test was done twice, once with the FLIR window and again with the IRISS window. The camera was then mounted on its side. The target mask was also rotated 90°, so that the simulated lug was in the same orientation to the camera lens as it was in the horizontal FOV test. The test was repeated, first using the FLIR window. When the target was moved left, this simulated the target moving down, as in a cable lug below the window in elevation. Consequently when the camera and target were returned to the center and then moved right, it simulated a target above the window. This measured the vertical FOV. This test was then repeated with the IRISS window. Figure 9 shows the camera rotated on its fixture and the mask rotated on the front of the blackbody source.

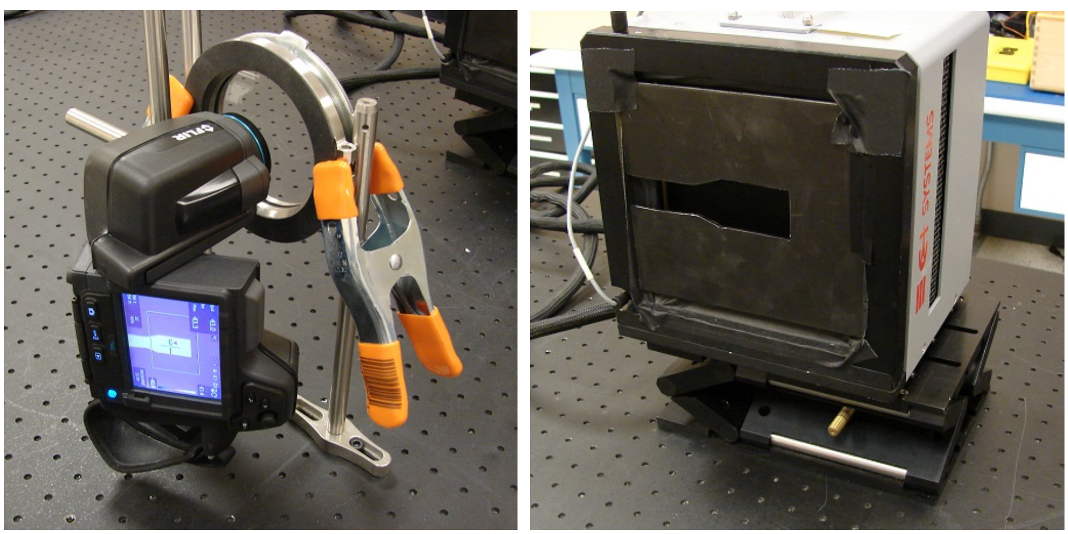

Figure 9 Camera and Target Mask Setup for Vertical FOV

Once the distance moved the target out of view, the camera was again rotated and moved to aim down or up to get the best view of the target. Measurements were taken with no window in place to establish a baseline temperature before each left or right test.

6.2 Test E Data

6.2.1 Horizontal Field of View – FLIR Window

The system was first tested with the FLIR crystal window. A test with no window established the temperature of the target at 55.2°C. Setting the transmissivity of the camera to 31% matched the no window temperature. Regular increments were used when the target was moved to the left. The motion to the right was only spot checked, to establish the limits. Table 7 shows the results of the Horizontal Field of View test with the FLIR window. The table presents the data from left to right, though the measurements were taken from the center outward to each side.

Direction	Distance From ctr (inches)	Spot (°C)	Notes
Left	38	51.7	Seeing temperature variations across target
	36	52.7	See partial window frame in image
	34	52.7	
	32	53.1	
	30	53.2	
	28	53.6	Moved spot location to center of target
	26	53.2	Camera about 60° to window face
	24	54.0	
	22	54.4	
	20	54.4	
	18	54.4	
	16	54.8	Camera about 45° to window face
	14	55.5	
	12	55.8	Only changed camera angle
	10	55.9	Only changed camera angle
	8	56.7	Moved camera back and angled it
	6	56.7	Only changed camera angle
	5	56.5	From this point on, move camera as necessary
	4	55.6	Camera fixed, target half out of frame
	3	55.6	Camera fixed, target toward edge of frame
Left	2	55.3	Camera fixed
Center	0	55.2	Camera straight on, Matched no window
Right	2	55.8	Tr set to 32% for measurements to right.
	3	56.1	Camera fixed
	4	56.1	Camera fixed, target half out of frame
	24	52.4	From this point, moved camera as necessary
	32	51.4	Only changed angle
	36	51.0	
Right	38	50.6	

Table 7 Horizontal Field of View, FLIR Window

With the camera fixed in place, the target was moved 4 inches to the side before it reached the edge of the image frame. At a distance of 18 inches, this corresponds to an angle = $\tan^{-1}(4/18)$ = 12.5°. This is the angle to one side, so the full FOV would be twice this, or 25°. This is equal to the standard lens HFOV for the T440 camera

The table shows the ability to see the target at a considerable distance to the side of the window once the camera was repositioned and angled. At the distance of 18 inches, at 38 inches to the side, the angle = $\tan^{-1}(38/18)$ = 64.7°. Total HFOV would be 129.4°. This is quite large and the resulting area that can be viewed from a single window approaches or exceeds the width of the cabinets under consideration. Internal obstructions would be the limiting factor.

It can be seen that at the far extremes, the reported temperature has dropped about 10% from the straight on measurement. This is likely due to attenuation caused by looking through more of the window material as the angle becomes shallower. As the thermal inspection is a comparative test, this lowering of the signal would not significantly alter test results.

Consider an arbitrary point where the temperature reading drops 5%. This has no reference to a practical inspection, but will provide a figure of merit to compare different windows. In this case, 5% of 55.2°C is 2.76°C, or a drop to 55.2°C – 2.76°C = 52.4°C. From Table 7, this occurred for the FLIR window at 24" on the right side, which is the smaller of the two. The angle at 24" is $\tan^{-1}(24/18)$ = 53.1°, or a HFOV of 106.2°.

6.2.2 Horizontal Field of View – IRISS Window

The Horizontal FOV test was repeated with the IRISS polymer window. A no window measurement established the target temperature at 55.8°C. A transmissivity setting of 49% provided a measurement of 55.7°C with the IRISS window in place. Based on the first HFOV test, not every increment was used to establish the widest FOV. Table 8 shows the resulting measurements.

Direction	Distance From ctr (inches)	Spot (°C)	Notes
Left	30	40.0	Target becoming obscured by window frame
	28	40.7	
	20	41.5	
	16	49.7	
	12	52.0	
	10	52.3	Moved and angled camera
	8	53.1	Only rotated camera
	6	52.3	From here on, moved and angled camera for best view
	4	54.4	Camera fixed. Target half out of frame
	3	55.9	Camera fixed.
Left	2	55.7	Camera fixed
Center	0	55.7	Grid lines not obvious in image
Right	2	55.4	Camera fixed
	3	54.0	Camera fixed
	4	53.8	Camera fixed. Target half out of frame
	6	54.0	From here on, moved and angled camera for best view
	8	53.5	Only rotated camera
	10	53.4	Moved and angled camera
	12	52.7	
	14	46.2	
Right	28	36.2	Variations in temperature across target

Table 8 Horizontal Field of View, IRISS Window

As a double check, when the left hand measurements were concluded, and the target still at 28 inches left of the center of the window, the window was removed and the transmissivity set back to 100%. The temperature recorded was 55.6°C, virtually identical to the straight on measurement with no window.

Fixed FOV again was at 4 inches to the side, as expected. The view to the side when the camera was moved reached 28 inches to the side (worst case). This represents an angle of $\tan^{-1}(28/18) = 57.3°$, or a HFOV of 114.5°. This is not as good as the FLIR window, but is still very wide.

The same drop off of temperature reading appears as the angle gets shallower to the window as was seen with the FLIR window, but it is more pronounced here for this polymer window. This may be due to the different material. The transmission of the polymer is higher than the crystal, but it may be of different thickness. Thickness of the windows was not specified. The larger dropoff is more likely from the reinforcing grid, which will obscure more of the signal as the angle gets shallower.

The 5% figure of merit for this window would be 5% of 55.7°C or 2.785°C, making the drop off point 55.7 – 2.785 = 52.9°C. From Table 8, this occurs at 12 inches to the side, or at an angle of $\tan^{-1}(12/18) = 33.7°$, or a HFOV of 67.4°, which is considerably less than the crystal window.

6.2.3 Vertical Field of View – FLIR Window

The camera and target were rotated 90° as described in the setup section above and the field of view test was repeated with the FLIR Window. This represented the vertical field of view since the target was moved up and down relative to the camera image. Table 9 shows the testing results with the FLIR window.

With the camera fixed, the target starts to leave the frame at about 3". This indicates an angle of $\tan^{-1}(3/18) = 9.5°$, or a VFOV of 19°, which corresponds to the stated VFOV of the T440 Camera.

The vertical field of view with the FLIR crystal window is nearly as good as the horizontal. The worst case distance was 36 inches above or below the center of the window, corresponding to an angle of $\tan^{-1}(36/18) = 63.4°$, or a HFOV of 126.9°.

The arbitrary 5% drop off in temperature occurs at 52.9°C. From the table, this occurs at 18 inches displacement or at 45° angle or 90° VFOV.

Direction	Distance From ctr (inches)	Spot (°C)	Notes
Up (Right)	38	47.8	Temperature variations across target
	36	49.4	Temperature variations at edge of image
	34	49.4	
	32	49.8	
	30	50.1	
	28	50.3	
	26	50.8	
	24	51.2	
	22	51.7	
	20	51.9	
	18	52.3	
	16	53.2	
	14	53.5	
	12	54.0	
	10	54.1	Only rotated camera
	8	54.5	
	6	54.9	
	4	55.3	Most of target out of frame. Move camera from here on
	3	55.4	Camera fixed. Top of lug out of frame
Up (Right)	2	55.5	Camera fixed
Center	0	55.4	Camera fixed and straight on
Down (lft)	2	55.4	Camera fixed
	3	55.8	Camera fixed. Only flat part of lug in frame
	4	55.4	Most of target out of frame. Move camera from here on
	6	55.6	
	10	55.0	
	14	54.2	
	18	52.9	
	20	52.4	
	28	50.0	
Down (lft)	36	48.7	Temperature variations across target

Table 9 Vertical Field of View, FLIR Window

6.2.4 Vertical Field of View – IRISS Window

The Vertical Field of View test was repeated with the IRISS polymer window. Table 10 shows the results of the testing.

Direction	Distance From ctr (inches)	Spot (°C)	Notes
Up (Right)	30	38.1	Target becoming obscured by frame and grid
	28	42.9	Spot on grid node (hot spot)
	26	46.7	Spot on grid node (hot spot)
	24	43.7	Variation due to grid
	22	47.5	Variation due to grid
	20	47.1	
	18	48.2	
	16	47.3	Variation due to grid
	14	51.1	
	12	51.9	
	10	52.3	
	8	52.7	
	6	53.5	Variation due to grid, but nothing distinct in image
	4	56.3	Most of target out of frame. Move camera from here on
	3	55.9	Camera fixed. Top of lug out of frame
Up (Right)	2	56.2	Camera fixed
Center	0	56.0	Camera fixed and straight on. Hard to see grid
Down (lft)	2	56.2	Camera fixed
	3	55.4	Camera fixed. Only flat part of lug in frame
	4	55.8	Most of target out of frame. Move camera from here on
	6	54.4	
	8	54.1	
	10	53.7	Spot on grid node (hot spot)
	12	51.2	
	18	47.6	Variation due to grid
	24	42.7	Variation due to grid
Down (lft)	28	36.2	Obscured by frame and grid

Table 10 Vertical Field of View, IRISS Window

As expected, with the camera fixed, the target leaves the frame at 3 inches displacement, or 19° VFOV, matching the camera.

The full VFOV is seen at 28 inches, or a corresponding angle of $\tan^{-1}(28/18) = 57.3°$, or a VFOV of 114.6°, which is less than the crystal FLIR window.

The 5% drop off figure occurs at 53.2°C, which occurs at 8 inches displacement, or at an angle of 23.9° for a VFOV of *47.9°. Again, using this arbitrary figure of merit, the IRISS temperatures drop off sooner than the FLIR temperatures. Note also in the table that the temperatures at the extremes have dropped considerably (23% if the last good readings at 28 inches) are used. The reinforcing grid is the most likely cause of this attenuation. In addition to that effect on the thermal measurements, the reinforcing grid causes issues when trying to take a visible image. Figure 10 shows the digital image taken at 28 inches in the Up direction, where a useful thermal image was obtained.

Figure 10 Digital Image through Polymer Window at Shallow Angle

The target can be made out, but it is largely obscured by the reinforcing grid.

6.3 Test E Summary

By angling and moving the camera for best view, the horizontal and vertical field of view through both windows was very large. It was large enough to span all of the width and most of the height of the representative electrical cabinets. Internal obstructions will therefore be a bigger factor in placing the windows in the panel covers. However, the large field of view will give more flexible options to avoid the internal obstructions.

The polymer window provided a smaller field of view in both directions than the crystal window. This was probably due more to the obstruction caused by the reinforcing grid on the polymer window. At angles closer to normal, the reinforcing grid makes some noticeable, but small difference in the readings. At shallow angles, when the target is much off to the side, the grid limits the angle at which it can be seen. In addition, the grid affects the visible images much more than the thermal.

Both windows exhibited a drop off in temperature readings as the target got farther away from the center of the window. In a comparative inspection, this drop off, at least for the crystal window, should not be significant. At the extreme edges of the polymer window, this drop off was severe. Therefore, the practical FOV would be more limited for the polymer window than for the crystal window. Again, this is most likely because of the reinforcing grid.

7 Test F – Simulated Fault – Side by Side Temperature Differences

In this test, two targets of different temperatures were placed side by side and a single image was taken with the camera. This simulated a fault in an electrical panel where one connection was running hotter than another connection in the same circuit.

7.1 Test F Setup

Two blackbody radiation sources were placed side by side. Their faces were masked with black tape, leaving an area the approximate size and shape of the connecting lugs on a representative electrical panel feed cable. Figure 11 shows the blackbody sources as set up for the test.

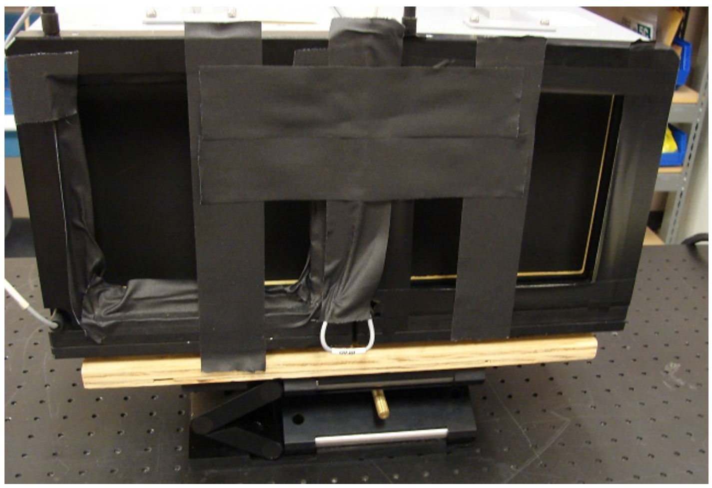

Figure 11 Two Blackbody Sources Masked to Simulate Panel Connections

The black tape in the center of the picture leaves open an area on the face of each blackbody source to simulate adjacent connections in an electrical panel. The area outside the taped portion is outside of the frame of the camera at the distance it was placed. The window was 18 inches from the face of the blackbodies and the camera lens was approximately one inch behind the window. The camera was fixed for all images during this test.

The blackbody source on the left was set for a higher temperature than the source on the right. The source on the right was set for 35°C. The temperature of the left blackbody was varied for each test, so as to present an increasing temperature difference between the two targets. The temperature of the left source was set at 40°C, 55°C, 75°C and 85°C. This represented temperature differences of 5°C, 20°C, 40°C and 50°C. To get one larger difference, in the last test the right blackbody was lowered to 25°C for a difference of 60°C. This represented the limit of the temperature settings of the two blackbody sources.

The camera was set for emissivity of 0.97. For each temperature setting, measurements were taken with no window and the transmissivity (Tr) set to 100%, with the FLIR window and Tr=31% and with the IRISS window and Tr=47%. The spot in the image was moved to each target in turn to get the reading.

7.2 Test F Data

Table 11 shows the temperature measurements and the calculated differences for each pair of temperature settings and windows.

Condition	Tr (%)	Left Spot (°C)	Right Spot (°C)	Difference (°C)
BB= 40°C Left, 35°C Right				5
No Window	100	40.2	35.1	5.1
FLIR Window	30	40.3	35.1	5.2
IRISS Window	47	40.5	36.2	4.3
BB= 55°C Left, 35°C Right				20
No Window	100	55.7	35.9	19.8
FLIR Window	31	55.9	34.7	21.2
IRISS Window	47	55.3	35.8	19.5
BB= 75°C Left, 35°C Right				40
No Window	100	75.8	35.9	39.9
FLIR Window	31	78.3	35.7	42.6
IRISS Window	47	76.0	36.7	39.3
BB= 85°C Left, 35°C Right				50
No Window	100	86.1	36.0	50.1
FLIR Window	31	89.8	36.0	53.8
IRISS Window	47	86.3	37.6	48.7
BB= 85°C Left, 25°C Right				60
No Window	100	86.0	26.0	60.0
FLIR Window	31	90.5	26.1	64.4
IRISS Window	47	85.8	28.0	57.8

Table 11 Simulated Fault, Side by Side Temperature Targets

By moving the spot location on the image, the temperatures of both targets could be measured without changing the camera position. The two targets appear in the same image, as would happen in a practical inspection. There were some differences in how close the measured temperatures through the window are to the temperature difference without the window, although the differences are small.

The higher temperature through the FLIR crystal window gets further off at the higher temperatures. This may be due to a transmissivity setting that was too low to start with. At the settings of 85°C and 35°C, a second test was made with the FLIR window, but the transmissivity set to 34%. In this reading, the left temperature was 85.6°C and the right was 35.2°C for a difference of 50.4°C. This suggests a higher transmissivity setting for the FLIR window in all the tests may have yielded results closer to the no window measurements.

Figure 12 shows the thermal image for the two targets set 20°C apart. In this image, the spot curser is over the left target.

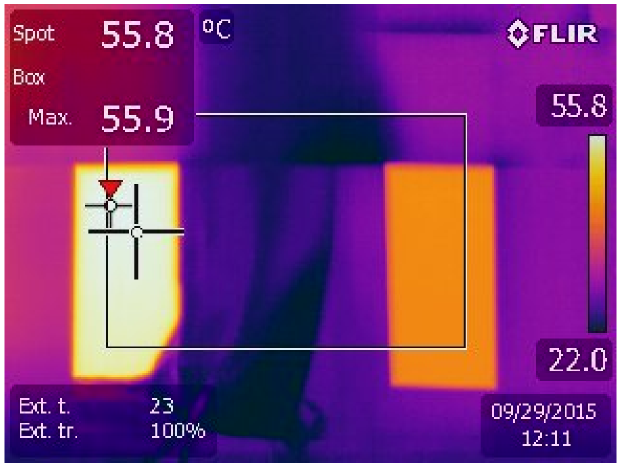

Figure 12 Thermal Image, Two Targets 20°C Apart, No Window

Figure 13 shows the same targets through the FLIR Window.

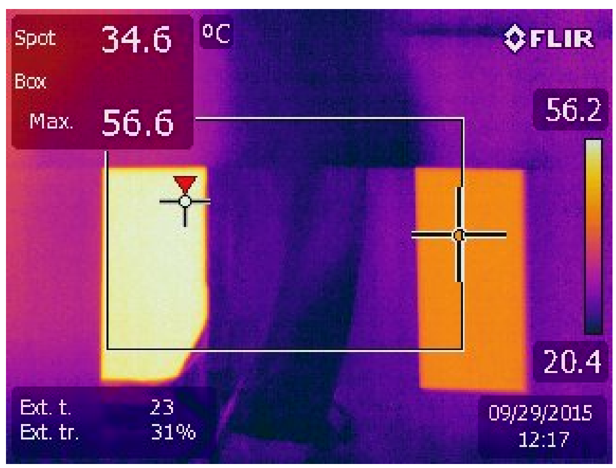

Figure 13 Thermal Image, Two Targets 20°C Apart, FLIR Window

In this image, the spot is on the right target, but the box covers both targets and therefore shows the maximum of the left target.

Figure 14 shows the same targets through the IRISS Window. Also in this image, the spot is over the colder target and the box is over the hotter target, so both temperatures are displayed.

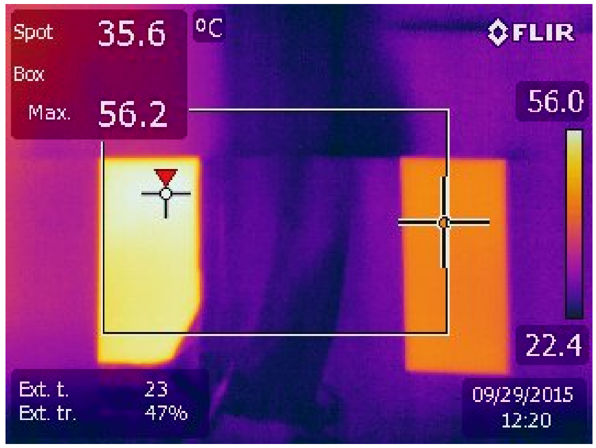

Figure 14 Thermal Image, Two Targets 20°C Apart, IRISS Window

7.3 Test F Summary

The camera is able to take an image of different temperature targets in the same view through both windows as well as with no window. The differences between the measured temperatures compared between the two windows were small. Where the difference was more significant, in the case of the FLIR window at higher temperatures, it could be accounted for by transmissivity setting of the camera.

8 Test G – Simulated Fault – Cable and Lugs

In this test, another simulated fault was set up using two samples of representative cable with connecting lugs on them. They were connected to copper bus bar and heated to different temperatures and imaged.

8.1 Test G Setup

The test setup is shown in Figure 15.

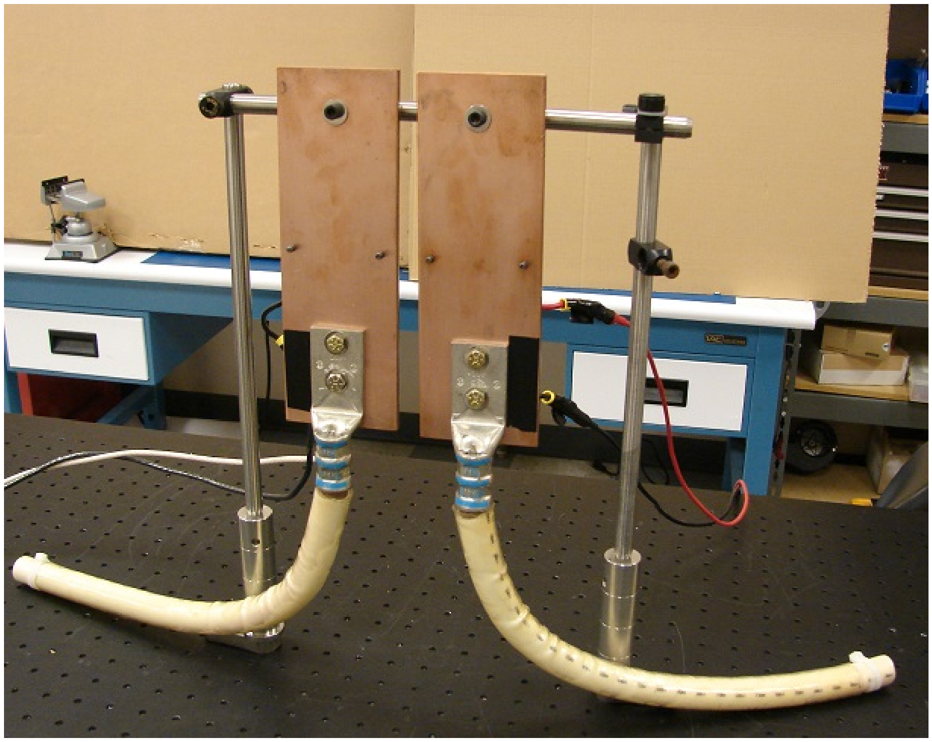

Figure 15 Simulated Faults, Cables with Lugs on Busbar

Two pieces of representative cable were bolted to ¼ inch thick copper busbar and suspended from a fixture over the optical bench. A 500 Watt 4.7 Ω power resistor was bolted to the rear of each busbar (see Figure 16). Each resistor was connected to a power supply that was set for a particular current. The power resistors acted as heating elements. After a time, the temperature of the resistors and consequently the busbar and the cable lugs stabilized. Heat Sink grease (thermal compound) was used between the resistors and the busbar and between the busbar and lugs to ensure better and more uniform heat transfer.

The piece of black tape adjacent to the lugs on the busbar was for setting the emissivity of the camera. By setting emissivity to a high number for the black tape (0.95) and measuring the temperature of the tape, the temperature of the lugs could be read and the emissivity set so that it read approximately the same temperature as the black tape. This method assumes the temperature of the tape is the same or very close to the temperature of the adjacent lug. As the heat transfer through the copper and into the lug is very good, this is a reasonable assumption.

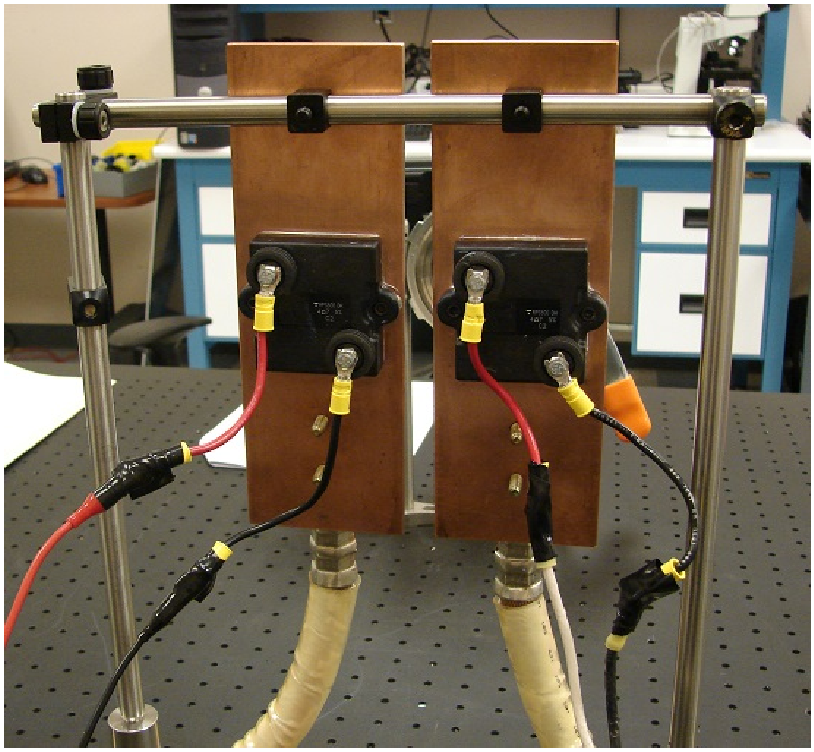

Figure 16 Power Resistors as Heaters on Rear of Busbars

For some of the first tests, a thermocouple was attached to the front of each lug at the bottom where it flares out to crimp onto the cable. This was an attempt to get a baseline temperature with which to compare the thermography measurements. However, it was discovered that the heat transfer to the thermocouple was not as efficient and the thermocouple was possibly sinking heat away from the lug and so the thermocouples were removed and the adjacent black tape method of calibrating emissivity was used for the later tests.

Different power supply settings were tried but settled on 2.8 Amps for the left lug, which yielded a temperature of around 79°C and 1.4 Amps for the right lug, which yielded a temperature of approximately 43°C. It took about an hour for the temperatures to stabilize.

8.2 Test G Data

The first attempt at this test yielded results that varied considerably. When setting the emissivity so that the temperature on the lug matched that of the adjacent black tape, the settings varied from 0.12 to 0.83. This was caused by the high sensitivity to the placement of the spot on the lug. Due to variations in the surface of the lug, the apparent temperature varied significantly at different spots on the lug. An alternate method was tried to set the emissivity. The cameras have emissivity tables built in for various materials. These lugs are tin plated copper and the closest setting was for polished copper or aluminum, at a setting of 0.05. Using this settings yielded temperatures well over 100°C, so the black tape method was used instead.

After further research and discussion with a Navy thermography expert, the test procedure was revised as follows.

First, the thermocouples were removed as they may possibly have influenced the temperature of the lug where they were attached, and uncertainties in the heat transfer from the lug to thermocouple cast doubt on their accuracy. Second, rather than use the camera spot crosshairs for measurement, the maximum temperature in the box was used. The box size was reduced so that it fit entirely on the cable lug. The box was further reduced for the last tests to eliminate any of the edges of the lugs. This reduced the sensitivity to the location on the lug where the measurement was taken.

The Navy acknowledges that there is a lot of variability in the surface texture and condition of the connecting lugs. Rather than rely on each operator's judgment as to where to set the camera emissivity, they use a uniform emissivity of 0.8. This allows comparison between tests done at different times and by different operators. As the inspections are all done on a comparison basis, they are less concerned about the accuracy of the absolute temperatures and more interested in the difference between the adjacent measurements.

The tests reported here were done with two methods. One used the black tape to set the emissivity of the lug, but with the maximum temperature in the box, rather than the spot measurement. The second method just set emissivity to 0.8 as per Navy procedure. Tests were run with no window at Tr=100%, the FLIR window at Tr=31% and the IRISS window at Tr=47%.

8.2.1 Emissivity by Adjacent Black Tape

Left power supply set to 2.8A. Right power supply set to 1.4A. After stabilization, with no window and the emissivity set to 0.95, the black tape adjacent to the left lug read 79.3°C and the tape adjacent to the right lug read 40.7°C.

With the box maximum on the left lug approximately equal to 79.3°C, emissivity was 0.49. With the box maximum on the right lug approximately equal to 40.7°C, emissivity was 0.55. Emissivity was set to 0.5, between the two readings but biased toward the hotter side. Table 12 shows the box maximum readings from the lugs for the no window measurement and with the two windows.

Window	Left max (°C)	Right max (°C)	Difference (°C)
Black Tape	79.3	40.7	38.6
No window	87.7	43.1	44.6
FLIR window	94.3	42.0	52.3
IRISS window	76.0	43.0	33.0

Table 12 Temperature Comparisons, Heated Lugs

This still shows considerable variation between the readings with the tape and the different windows. Figure 17 shows the thermal image of the two lugs, with the box centered on the right lug.

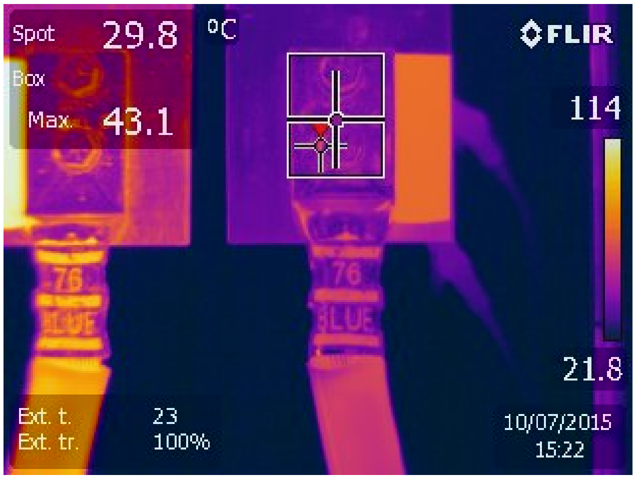

Figure 17 Thermal Image of Heated Lugs, No Window

The camera and window were moved 5 inches to the right so viewing the lugs would be at an angle. This also reduced the likelihood that reflections were being seen in the lugs. Emissivity was kept at 0.5 and the test repeated. Table 13 shows the results.

Window	Left max (°C)	Right max (°C)	Difference (°C)
No window	82.0	38.7	43.3
FLIR window	83.8	38.8	45.0
IRISS window	80.0	37.7	42.3

Table 13 Heated Lugs, Camera at Slight Angle

Results are more consistent.

The third test kept the camera and window 5 inches to the right, but used a smaller box on the lug to avoid the edges, which sometimes showed hot spots. Emissivity was still 0.5 and table shows the results.

Window	Left max (°C)	Right max (°C)	Difference (°C)
No window	71.9	40.7	31.2
FLIR window	72.7	39.8	32.9
IRISS window	62.2	37.7	24.5

Temperatures for the higher lug are lower. This suggests that the smaller box may be eliminating hot spots (particularly along the edges of the lug). The smaller difference with the IRISS window is seen to be from the lower temperature on the left lug.

Figure 18 shows the thermal image with the smaller box on the left lug.

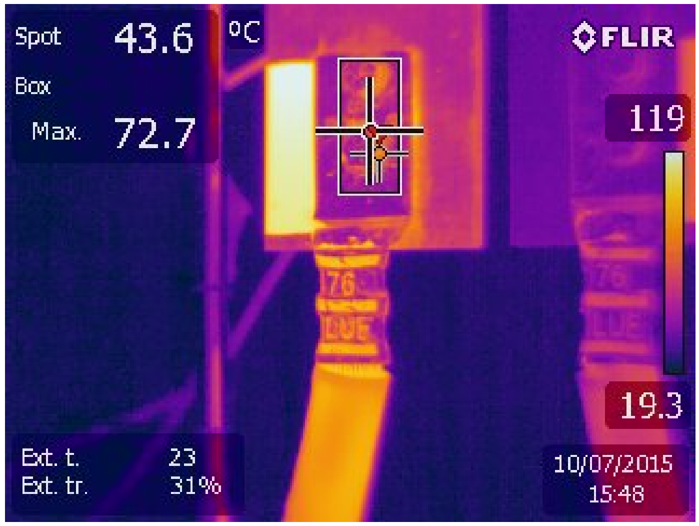

Figure 18 Heated Lugs, Smaller Measurement Box

It is hard to draw conclusions from these three tests, but the box method with the smaller box showed more stability between measurements and it was decided to use the smaller box for the remaining test.

8.2.2 Emissivity Set to 0.8

The final test set the emissivity of the camera to 0.8 per Navy procedure. The camera and window were returned to their straight on positions. Transmissivity for the windows was kept as in the previous tests. Table 14 shows the results.

Window	Left max (°C)	Right max (°C)	Difference (°C)
No window	60.5	35.2	25.3
FLIR window	67.2	34.7	32.5
IRISS window	53.7	35.2	18.5

Table 14 Heated Lugs, Emissivity Set to 0.8

Temperatures are again lower, particularly the hot lug through the IRISS window.

8.3 Test G Summary

These tests show comparative measurements can be made through the different windows. The test setup is not a perfect simulation. With no current flowing through the cable and lug, the heat buildup in the lug is not the same mechanism as would be in a real test. The lugs here were heated externally and the heat at the surface being measured was dependent on the heat transfer through the materials and interfaces. Therefore, it is hard to draw firm conclusions based on the numbers, particularly since there was variation between the tests.

The Navy already recognizes that variations in the surface geometry and condition of the connection lugs being imaged affect the emissivity of the surface and hence the temperature measurement. They therefore specify a setting o 0.8 for emissivity for all tests. These laboratory tests have also shown some variation of a few percent in transmissivity settings to get identical temperature results when using IR windows. For a practical inspection using windows, techniques and procedures will need to be developed that take into account these variations in emissivity and transmissivity. These techniques will select settings that err on the side of caution (allow more false positives rather than false negatives).

9 Test H – Imaging with Rubber Dust Boot

Recent panel designs include a protective rubber (exact material unknown) dust boot over the bus bar connections. As it is likely that this boot will affect thermal imaging of the bus connections, a sample of the boot was obtained for use in these laboratory tests.

9.1 Test H Setup

The geometry of the test setup with heated lugs does not match the design of the rubber boot sample. Therefore, the boot material was fixed over the front of the test fixture in Figure 15 so that the cable lugs were covered. One side of the boot is shaped to give space underneath it for the lug connections. The other side has some space, but sits flatter to the bus bar.

The actual emissivity of the boot material was not known, but nonmetals usually have high emissivity. Emissivity was set to 0.95 and the boot was imaged as it lay on the optical table at ambient (23°C) temperature. The readings from the camera were 23 - 24°C. In addition, the black optical table adjacent to the boot read 23.2°C. It was concluded that 0.95 emissivity would be sufficient.

The boot was attached to the fixture both ways. With the shaped side in front of the lugs, there was about 2 inches of air gap between the hot lugs and the boot. With the flatter side, the air gap was about ½ inches, and it was contrived to have the boot material touching the lug in another test.

Imaging through the boot was problematic (see next section), so attention shifted to the cables exiting beneath the boot material. Black tape was placed on the left cable about 2 inches below the lug. This tape was not visible on the thermal image, suggesting that the emissivity of the cable jacket is quite high. With emissivity set to 0.95, the tape was not visible on the cable.

With emissivity at 0.95, temperatures were taken at a piece of black tape on each lug to get a reference on the lug temperature. Temperature readings were then taken on the two cables below the lugs. The test was repeated through the FLIR window.

9.2 Test H Data

Figure 19 shows a thermal image of the boot material covering the heated lug.

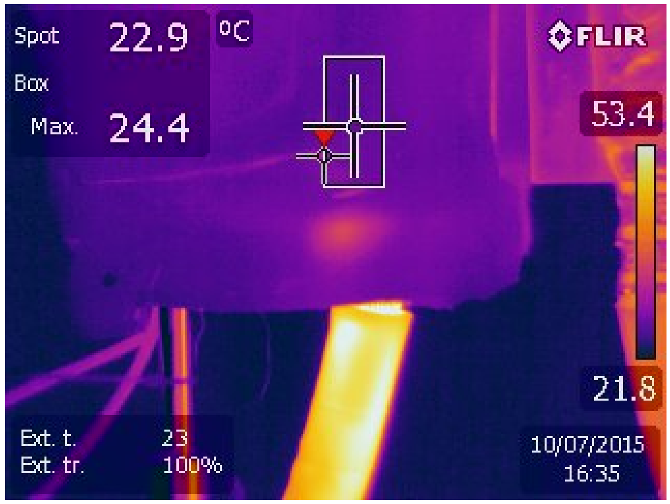

Figure 19 Thermal Image of Boot Material Covering Heated Lug

What looks like a hot spot located over the hot lug is evidently a reflection. It moves when the boot material is moved or when the camera is moved. Several configurations were examined and none of them showed what could be interpreted as an actual thermal measurement from the surface of the boot.

The above measurement was taken within several minutes of the boot being placed over the heated lug. With the boot unable to be snugly placed over the lug as would happen in an actual installation, and the rear of the busbar open to the air, there was nothing to contain the heat from the busbar. In addition, the air gap provided sufficient insulation to prevent heat transfer to the boot material.

The boot material was then positioned over the heated lugs and secured so as to minimize the air gap. A backing plate behind the busbar, and tape over the side caps provided a means to contain the heat from the busbar inside the boot. In addition to this, the setup was left energized for up to six hours to allow the heat to be transferred to the boot. Figure 20 shows a picture of the setup. This test was done with no window and the transmissivity set to 100%. Also, to get the entire area of interest in the same field of view of the image, the camera was moved back to 27” distance from the target.

Figure 20 Boot Material Jury Rigged over Heated Lug

The setup was examined approximately 4 hours and 6 hours after being energized. Measurements were taken at several points across the surface of the boot material. There was no significant difference between the measurements taken at 4 hours and those taken at 6 hours. After the last measurements were taken, the boot material was removed and the black tape adjacent to the left lug and the right lug was measured to get a number for the connection temperatures. Several actual hot spots were visible in the thermal image as shown in Figure 21.

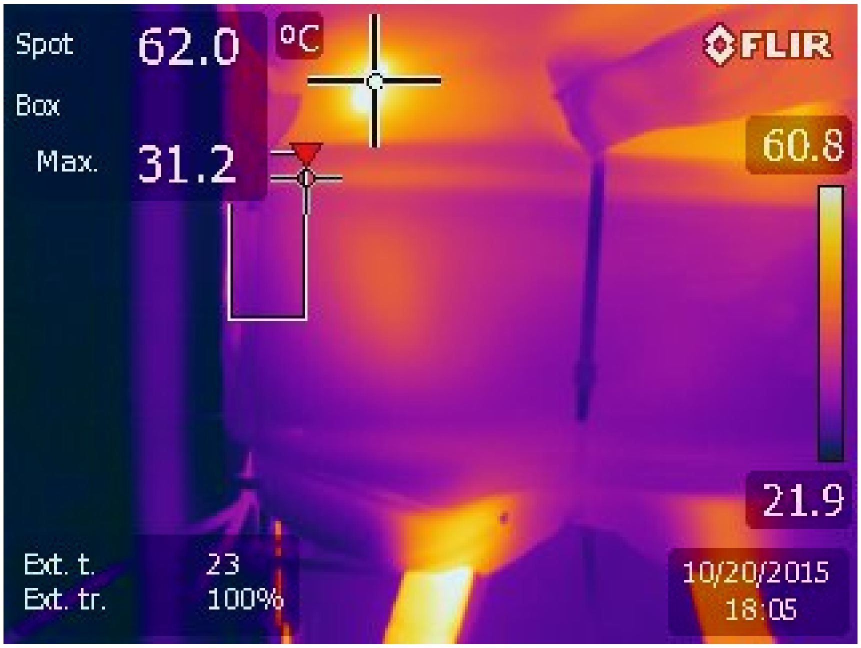

Figure 21 Thermal Image of Boot Material Over Heated Lug

In the figure, several areas of elevated temperature can be seen. The brightest spots on the boot material (just above where the left cable comes under the boot material, and at the top left are where the boot is closest to the hot surface, that is, where the air gap is lowest. Even where there is a larger air gap, elevated temperature regions can be seen over the left lug, and at the top of both lugs. The temperature over the cooler right lug was measured at about 27°C, or just several degrees above ambient. Table 15 shows the measurements at various points in the image.

Measurement Location	Spot (°C)
Left cable below boot	62.3
Boot just above left cable entry	52.7
Right cable below boot	35.7
Boot just above right cable entry	33.3
Hot area in middle where left lug is located	31.8
Middle where right lug is located	26.8
Hot spot above left lug	67.5
Hot spot above right lug	41.1
Tape adjacent to left lug (no boot material)	85.7
Tape adjacent to right lug (no boot material)	45.8

Table 15 Temperature Measurements of Boot Material Over Heated Lugs

The figure and the table both show high temperatures on the left boot, over the hotter of the two cable lugs. The actual temperatures measured are still about 20°C lower than the temperature of the lug beneath it. In the middle of the boot over the left lug, the temperature is only 5 °C hotter than over the lug on the right. Nevertheless, a difference is noticeable. This test was hampered by the mismatch of the boot design with the jury rigged test setup, which prevented a snug fit of the boot over the connections. Where the boot was close or touching the hot surface, much more heat was present at the outside of the boot.

A second test focused on the cables as they exited the boot. With no window, the temperatures were measured on the left lug (black tape), the left cable insulation below the lug, the right lug (black tape) and the right cable insulation below the lug. Table 16 shows the results.

Measurement	Temp (°C)
Left lug black tape	71.1
Right lug black tape	37.0
Temperature difference at lugs	*34.1*
Left cable insulation	50.2
Right cable insulation	31.4
Temperature difference at cables	*19.0*

Table 16 Temperature of Cables Below Lugs, No Window

Since the source of heating was on the other side of the bus bar, the heat transferred down the cable was noticeably less, resulting in lower temperatures read off of the cables, and a corresponding smaller difference between the left and right measurements.

This test was repeated with the FLIR window in place and the camera transmissivity set to 32%. Table 17 shows these results.

Measurement	Temp (°C)
Left lug black tape	71.3
Right lug black tape	35.4
Temperature difference at lugs	*35.9*
Left cable insulation	48.9
Right cable insulation	29.8
Temperature difference at cables	*19.1*

Table 17 Temperature of Cables Below Lugs, FLIR Window

With the FLIR window in place, the differences are almost identical.

Figure 22 shows a measurement of the cables below the boot material with the measurement box on the hot cable on the left and on the cooler cable on the right. No window was used. The temperature difference of 54.6°C minus 33.0°C is 21.4°C, similar to previous results.

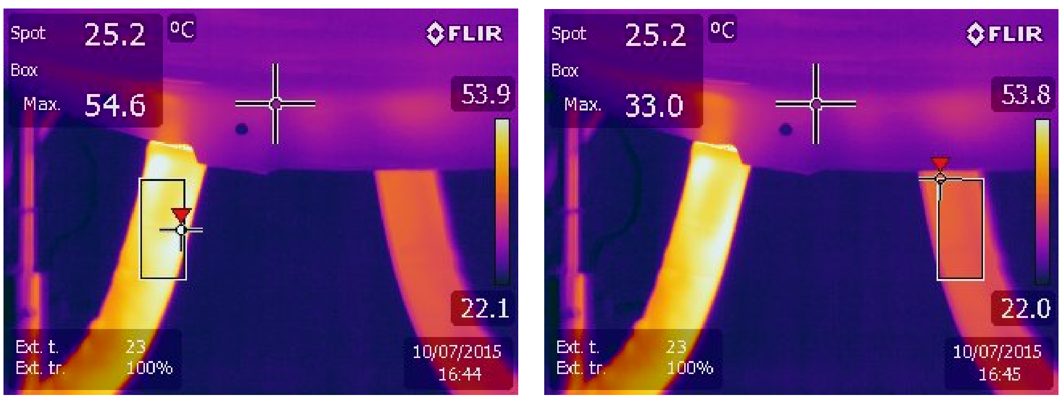

Figure 22 Cable Temperatures Measured Below Rubber Boot

Figure 23 shows a digital image of the dust boot material covering the connections but not the cables.

Figure 23 Dust Boot Material Over Heated Lugs

9.3 Test H Summary

These tests confirmed that while the rubber boot material affects the measurements, it may be possible to get useful temperature readings through the boots. When the boot was secured tighter to the connection, and the system was left to sit at temperature for a period, enough heat was transferred to boot to be evident in the thermal image. Temperatures were significantly lower than the actuals underneath the boot, but a definite difference between the temperatures over the hotter connection lug and the adjacent cooler lug. It is also possible to see marked temperature differences in the cables as they exit from beneath the boot.

It was not possible to get definitive measurements due to the test setup itself. The boot material did not fit snugly over the heated connections and had to be jury rigged. This led to larger than normal air gaps between the connection and the boot and places for the heat to escape the boot. Also, the heating source was on the back side of the busbar that the cable lug was connected two, so there were some losses in heat transfer between the heating source and the busbar, the busbar and the lug, and the lug to the cable. Also, the boot material and the cable insulation provided some thermal insulation as well. A test on an actual panel installation would determine how close the cable temperatures are to the connection temperatures.

Even with the heat transfer losses, the difference between the boot over the two different temperature lugs, or the two cables is noticeable in the thermal image as well as in the measurements. It is quite evident that one of the connections is significantly hotter than the other. This would be enough to alert an inspector that there is an imbalance between two of the phases. Imaging through an IR window made no difference.

10 Test I – Visible Imaging along with Thermal Imaging

A visible image is typically taken along with the thermal image to put the thermal measurements in context and identify which connections are being measured. Most modern thermal cameras have the ability to take a visible (digital) image as well as the thermal image. The FLIR T440 can take both images at the same time. This test examined some of the issues imaging through the windows using the digital camera built into the FLIR thermal camera.

10.1 Test I Setup

Images were taken of the heated lugs under different circumstances. First with no window, then the FLIR window was inserted and transmissivity set to 31%. The visible camera lamp was turned off and an image was taken through the IRISS window with Tr= 47%.

The room lights were turned out to simulate that the targets were inside a panel with the cover on and very little light coming through the IR window port. The camera lamp was turned back on and additional images taken through the FLIR window and the IRISS window.

10.2 Test I Data

Figure 24 shows thermal and digital images taken at the same time through the FLIR window. The room lights were on, so the targets were illuminated externally. The digital camera lamp was off.

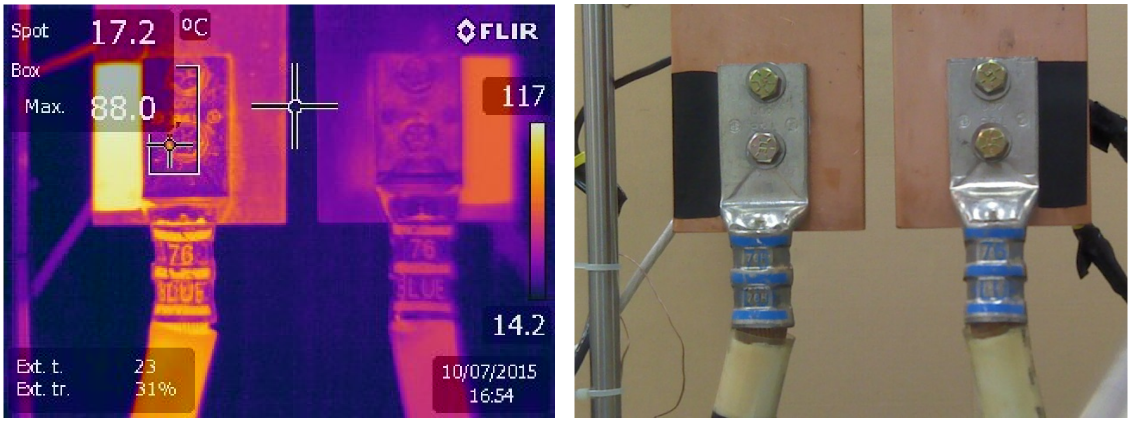

Figure 24 Thermal and Digital Images, FLIR Window

Figure 25 shows the same measurements through the IRISS Window.

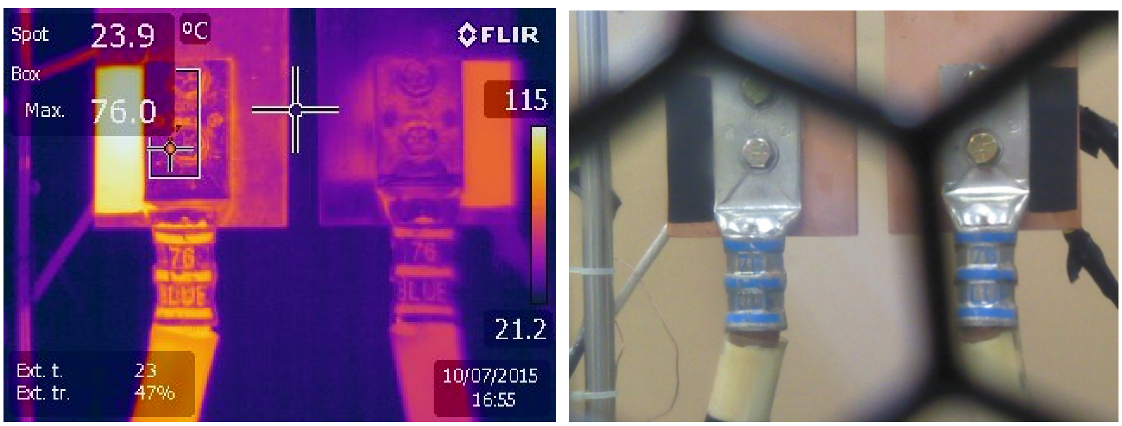

Figure 25 Thermal and Digital Images, IRISS Window

It can be seen that the reinforcing grid on the polymer window affects the digital image, where it does not affect the thermal image. Additional digital pictures were taken through the IRISS window and are shown in Figure 26.

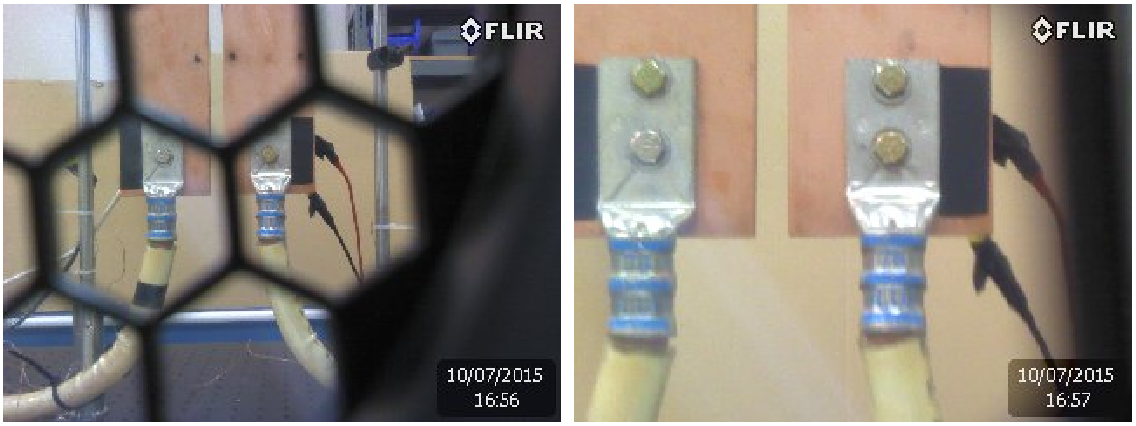

Figure 26 Digital Images Through Polymer IRISS Window

With some maneuvering, the camera can be placed so that the grid lines do not interfere with the image, as seen in the right most picture in Figure 26. However, note that these images were taken with the camera lamp off and illumination coming from the overhead lights.

To simulate imaging in a closed cabinet, the room lights were turned off and the window removed. The thermal image is as normal, but the digital image is completely black. The camera lamp was turned back on. Figure 27 is the image with no window, but all illumination coming from the lamp on the camera.

Figure 27 Digital Image with only Camera Illumination

This is adequate for illumination purposes, but the lighting is not very uniform.

Figure 28 shows the thermal and digital images through the FLIR window and with the camera lamp turned on.

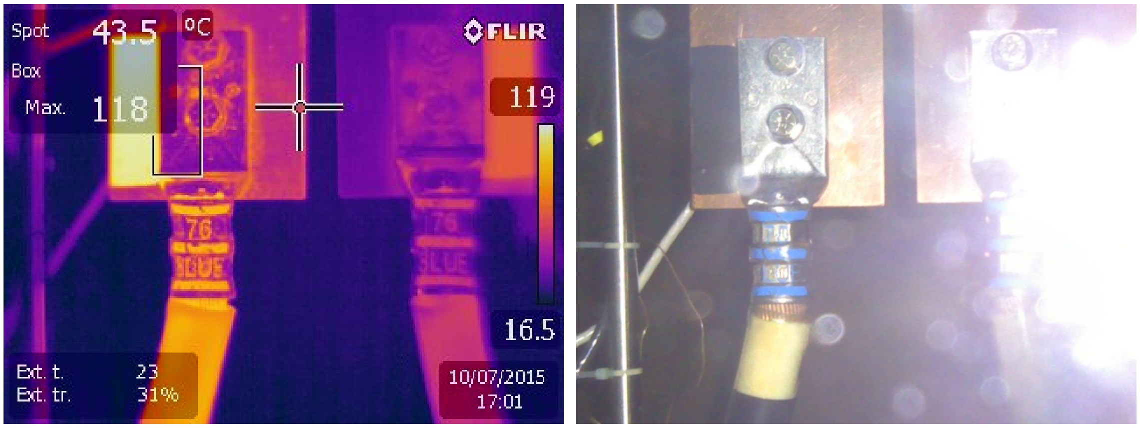

Figure 28 Thermal and Digital Images, FLIR Window, Lamp On

It can be seen that there is considerable reflected glare on the window in the digital image.

Figure 29 and Figure 30 show digital images through the IRISS Window with the room lights off and the camera lamp on.

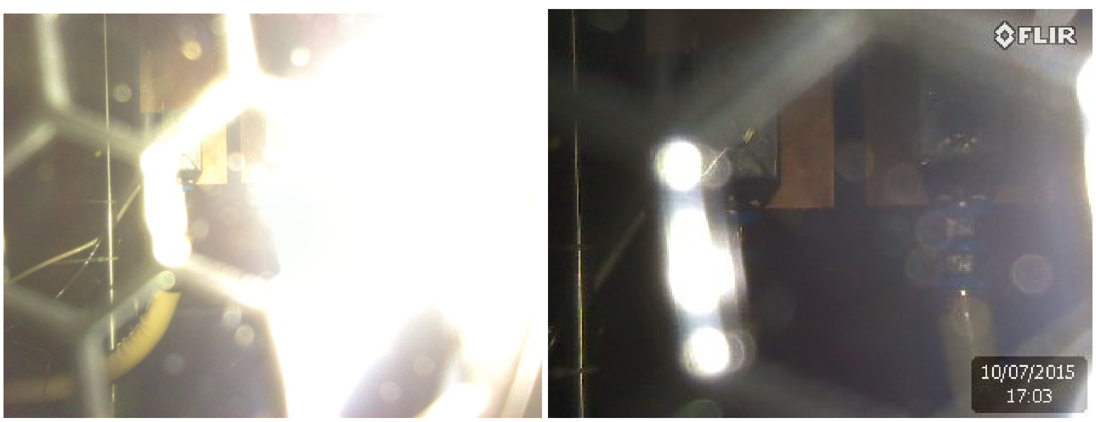

Figure 29 Digital Images through IRISS Window, Lamp On

Figure 30 Digital Image through IRISS Window, Lamp On

Even with maneuvering of the camera (Figure 30), the reinforcing grid and subsequent reflections off of portions of it make it difficult to get a good image of the target area.

10.3 Test I Summary

Provided the lighting is good, there is no problem taking digital images through the crystal window. Images can still be taken through the reinforcing grid on the polymer window, but the camera must be placed and aimed correctly to minimize the obstruction provided by the grid.

Without external lights, both windows had a problem. The reflected light off the window from the camera's own lamp affects the image, sometimes severely. It may be necessary to illuminate the interior of the panel with a light or lamp from another port or other opening, or it may be possible to hold a flashlight very close to the window, so that reflected light goes back into the flashlight and not into the camera lens. This was not tried, however.

11 Conclusions

The objective was to evaluate thermal imaging through IR Windows under laboratory conditions and to compare the two main types of available windows: crystal and polymer. The most significant things learned were:

- Reasonably accurate temperature measurements can be made through IR windows provided attention is paid to emissivity and the window transmissivity settings in the camera. Even under the best controlled conditions, there was some variation in the transmissivity settings between tests and from day to day to obtain the same temperature readings as when there was no window present. These variations were only of a few percent, but will need to be taken into account when developing procedures for proper inspection with windows. As the thermal inspection is a comparison test, which notes the difference between measurements on different phases of the same circuit, the absolute temperature readings are less important. If a common transmissivity setting is selected for all crystal windows, for example, then the small variations noted in these tests will not affect the comparison measurements, since they will apply to both measurements and be subtracted out when the difference is calculated.

- Variations in target (cable lugs) surface geometry and condition make the measurements very sensitive to the location of the measurement point in the image. This is a known issue and the Navy compensates for it by using a standard emissivity setting for all tests. As the inspection is a comparative test, the absolute measurements are not important compared to the difference between them. Some of this variation can be accounted for by the setup, which heated the connections externally, rather than from the current passing through the joint. These issues can be minimized by developing uniform techniques and procedures to provide a useful comparison test.

- The windows provide an extremely wide horizontal and vertical field of view allowing visual access to most of a cabinet through a single window, limited only by internal obstructions. This will allow more flexibility in the placement of the window(s) in the panel and fewer or smaller windows.

- The polymer windows all have a reinforcement grid behind the viewing surface. This is present but does not affect the thermal measurements in a significant way. However, it does reduce the field of view compared to the clear crystal window and it affects visible images taken through the grid. Some polymer windows are translucent, which precludes taking visible images at all. While thermal imaging can be correctly performed through the polymer windows, they have these disadvantages compared to the crystal windows.

- The rubber boot material that covers bus connections in current panels does affect the temperature measurements. However, if left to stabilize, it is possible to note differences in the thermal image that indicate a problem in the connections beneath the boot. The cables exiting beneath the boot also show significant temperature differences.

- Reflected glare off both windows affects visible images taken with the camera's own illumination source. As the intent of the window is to allow viewing with the panel cover closed, some other method of illuminating the interior will be needed.
- Thermal imaging can be conducted through both the crystal and polymer windows. The lower transmissivity of the crystal window was not a factor in making measurements. The crystal windows performed better in the field of view tests. The reinforcing grids behind the polymer windows only affect the thermal imaging when the camera is at a shallow angle to the window (looking off to the side) and in taking visible images. Based on these tests, crystal windows would be recommended.

Regarding the individual tests, the following items were determined:

Most of the tests used a blackbody radiation source to generate a heat source at a known temperature with a known emissivity. A baseline was established using two thermal imaging cameras, a FLIR T440 and a Fluke TI32. Both cameras imaged correctly. The FLIR camera was chosen for the remainder of the tests as it is a similar model to that used in the Navy for panel inspections, and had a better feature set for the tests.

Four representative IR windows were evaluated: two crystal windows and two polymer windows. All four allowed infrared imaging through them at varying rates of transmission. Reasonably accurate temperature measurements were obtained once the transmissivity setting in the camera was adjusted to match the window. The two crystal windows were virtually identical in performance. The FLIR window was used for the remaining tests since it most closely meets the preliminary specification for the electrical panels for LHA-8. The two polymer windows were quite different. The square Exiscan window was translucent, which precluded visible spectrum pictures through it and also made focusing of the thermal image difficult. It was discarded in favor of the IRISS polymer window, which was used in the remainder of the tests. The reinforcing grid of the polymer window did affect some of the later tests.

Images were taken through the one crystal and one polymer window across the full range of the blackbody radiation source. Measurements were able to be taken through both windows although there was some variation due to transmissivity settings in the camera. Different tests on different days required the transmissivity to be set a few percentage points different than on previous tests.

Horizontal and vertical field of view was evaluated through both windows. Both windows had very large fields of view, with the crystal FLIR window having a field of 129° H by 127° V and the polymer window being 115° x 115°. From typical distances from the panel to the switchgear being imaged, this would mean the camera can see all of the cabinet from side to side and most of the cabinet up and down from a single window. The limiting factor would be internal obstructions. This large field of view also allows for more strategic placement of the windows in the panel covers. The polymer window was not as good as the crystal, which may have been material related, but was more likely due to the reinforcing grid on the polymer which was more and more intrusive as the camera angle became shallower.

Some simulated panel faults were evaluated. There was no trouble taking images and making measurements through either window on a target consisting of two blackbody radiation sources sat side by side and set to different temperatures. A second simulation involved actual cables with connecting lugs bolted to a piece of busbar. The busbar was heated from behind with a resistance heater. Two adjacent cables and lugs were heated to different temperatures to simulate a panel fault.

With the actual cable lugs, the measurements were very sensitive to the emissivity setting and the placement of the measurement indicator. This was due to the natural variations across the surface of the target that affected emissivity. As a panel inspection is a comparative test, the actual emissivity settings and subsequent reported temperatures are not as important as absolute values. It is the difference between them that counts and if the measurements are taken under the same conditions, the comparison will be valid. The same reasoning applies to the transmissivity setting of the camera to account for the window material.

The rubber boot material used as a dust cover on connections in recent panels does affect thermal measurements of connections behind the boot. Only indirect measurements can be made, either of the heat transferred through the boot material over time or of the cables as they exit below the boot. However, sufficient heat appears in the thermal images to determine if there is an imbalance between two different connections in the same circuit. Further investigation without the boots may be necessary to determine the actual extent of the imbalance. Physical issues with matching the test setup to the sample boot affected the measurements. It is expected that in an actual installation, measurements closer to actual and more indicative of a connection fault will be obtained through the boot material.

Visible images were taken through both windows using the camera’s digital imager. If there was sufficient lighting, good images were obtained through both windows, although the camera had to be maneuvered with the polymer window to avoid obstructions in the image from the reinforcing grid. With the ambient light off and the only illumination from the camera’s own lamp, there was reflected glare using both windows that affected the images taken. A separate light source would be needed to compensate for this.

Safer Inspection of Medium Voltage Electrical Panels on Navy Ships

The National Shipbuilding Research Program

2015 Electrical Technologies Panel Project

Field Test Report

March 24, 2016

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Executive Summary

Previous laboratory tests, performed in the Fall of 2015, examined the use of infrared thermography through IR transparent windows in a controlled setting. Follow-on field tests were performed in February 24 and 25, 2016 at DRS Power and Control Technologies in Milwaukee, WI. The purpose of these field tests was to determine the effectiveness of IR windows in a representative shipboard electrical panel and identify issues that would be relevant in this setting. Members of the Integrated Project Team and other stakeholders were on hand to observe the tests and provide perspectives. DRS had built a prototype 4160 Volt cabinet of the type relevant to this project and offered it as the test fixture along with their testing facility. In this facility, the cabinet was energized with low voltage, high current to simulate the temperature build up at the connections inside the cabinet. A benefit of this method was that faulty connections could be simulated by loosening a cable connection. This would not have been possible on a cabinet energized at 4160V due to concern of a potential arc fault.

Two different IR crystal window sizes were used, along with two different thermal cameras. DRS had provided the prototype cabinet with a fixture on the back that permitted the IR windows to be placed in various locations. Both infrared thermal imaging and visible imaging (for context) through the windows were performed. Tests were also performed using samples of the dust boot material that is installed in every 4160V cabinet to protect the connections from buildups of dirt and grime that can lead to short circuits.

The most significant things learned were:

1. Thermal imaging through windows in a panel can be done with proper attention paid to camera settings. Normal and faulty connections were imaged with faulty connections plainly evident by the higher heat produced across the connection compared to normal connections.

2. Thermal imaging through windows is fundamentally not much different than imaging through an open panel cover. However, adjustments to procedures will need to be made. The most significant issue is setting the camera to compensate for the attenuation of the light through the window. Other practical issues regarding how much can be imaged through the field of view and the need for supplemental illumination also need to be taken into account. New procedures will have to be developed for practical tests to account for these factors, including a new “star chart” for reference to severity of fault conditions. Some of the thermal imaging cameras have features that might be helpful when developing new procedures, such as multiple measurement areas, difference measurements, and annotated reports generated in the camera.

3. Internal obstructions are the biggest issue for imaging through windows. By angling the camera to the window, the field of view is sufficient to see anywhere in the cabinet from one window in the top and one in the bottom, were it not for internal obstructions. Cables running from the bottom to connections at the top and the brackets that hold them can obscure connections near the bottom. The nature of the bus bars (vertical between cabinet halves and horizontal between cabinets) mean that some connections will be obscured.

This will be a design challenge for the cabinet manufacturer, to minimize the number of internal obstructions and optimize the placement of the windows. It may be more advantageous to include more windows to provide better line of sight to all internal connections.

4 The dust boots that cover all connections within the 4160V cabinets definitely affect thermal imaging. Two dust boot materials were tested, but neither was designed for this particular cabinet. The existing boot materials are not transparent to infrared wavelengths. Therefore, detecting a faulty connection requires that the heat from the connection be transferred to the boot, and then the hot spot on the boot surface can be measured.

In this case, proper fit and location of the dust boot makes a difference. The more air gap there is between the connection and the boot surface, the less heat gets transferred. The most evident hot spots in the thermal images were where the boot material was very close or touching the hot connection. Design of new boot covers that are transparent to IR wavelengths is an area worth further investigation.

5 Alternately, given that it will be hard to tell how much heat is being transferred to the boot material, it may be better to image the cables as they enter or exit beneath the dust boot. The cables have a more uniform emissivity than the connections themselves. The dust boots can be designed so that the cables exit from the boot not far from where the cable lug is bolted to the bus bar. These tests show that the cable to a faulty connection is considerably hotter than adjacent cables with good connections and well evident in the thermal images. Some additional research would need to be completed to determine the amount of temperature loss down the cable, so as to get reliable temperature measurements and redefining the criteria in the “star charts”. If this method is chosen, then it would be better to select window locations in the panel cover that afford view of the cables rather than the connections themselves, which will be covered by the boots.

6 While it may be desirable under production circumstances to use a simpler IR camera with fewer features, the camera should at least have the ability to account for the transmissivity of the window. Otherwise, the reported temperatures will be too low by a large margin (as seen in the Fluke TI10 images) and the differences between faulty connections and normal connections may not be large enough to generate an error condition.

7 Supplementary illumination will be needed to take visible images for context with the IR images. With no illumination at all, the interior of the cabinet is too dark for visible photography. The built in lamp with the camera sometimes allows adequate pictures but often creates a reflection on the window that obscures part of the image.

Best results appeared to be when an auxiliary light (flashlight) was shown in the window adjacent to the camera lens, or through another opening nearby. That opening could be a second IR window, if it was deemed necessary for avoiding line of sight obstructions. A lamp through a window at the top of the cabinet was inadequate to illuminate the target at the bottom of the cabinet and vice versa. Lighting built into the cabinet would solve the problem, but that would be a design issue for the manufacturer.

The practical tests mostly confirmed what was learned in laboratory testing. See Laboratory Test Report, October 23, 2015 for more information.

Additional items regarding the practicality of doing thermal inspections through the windows were noted during the tests. These are listed in the test summary section at the end of the report.

Introduction

Previous laboratory testing examined certain aspects of performing infrared thermography in an electrical switchgear panel through an IR transparent window. The purpose of this set of field tests was to perform IR thermography through IR windows in a relevant field test setting and determine any issues particular to installation on electrical panels. These tests were originally planned for testing on actual installed panels on board ship on LHA-8. However, events outside of this project caused the window for this opportunity to slip beyond the period of performance of this contract. DRS Power and Control Technologies offered use of their prototype 4160V electrical cabinet at their facility in Milwaukee, Wisconsin for experimentation and characterization. These tests were performed on February 24 and 25, 2016 at the DRS factory in Milwaukee.

The DRS prototype cabinet was of a nearly complete design and considered representative for the purposes of these tests. Some features within the cabinet were absent while others were simulated. The cabinet was not energized at 4160V for safety reasons. Instead, low voltage at high current was passed through the connections in the cabinet. This heated the connections sufficiently to provide realistic targets for the IR thermography. For part of the testing, a cable was loosened to simulate a faulty connection. Two different size crystal windows were used with two different IR cameras. DRS provided a fixture on their cabinet that permitted the window to be placed in one of 8 locations vertically along the rear panel cover.

The main connections of interest were where the power to the cabinet is connected by the shipyard. These are across the cabinet at the top and across the cabinet at the bottom. The secondary connections of interest are in the middle of the cabinet, where three bus bars (one for each phase) would be connected horizontally to adjacent cabinets in a shipboard installation. Once the ship is in service, these connections would need to be periodically examined as well. As there was only one test cabinet, these connections were not made for these tests.

This report describes the testing and the results.

1 Test Setup

DRS fabricated a 4160V electrical cabinet for their own IR&D purposes and made it available for this project. The cabinet is a prototype in that it does not represent the complete final design of the cabinet. However, it is representative of typical 4160V cabinets. Also, not every feature was ready at the time of the testing and consequently a few components were not installed. DRS also provided the test facility. This primarily included the ability to simulate normal operation by running current through the connections.

1.1 Cabinet

A rear view of the DRS cabinet is shown in Figure 1.

Figure 1 DRS Test Cabinet - Rear View

The cabinet is 81” high by 23” wide by 54” deep. The cabinet is designed to hold three circuit breakers in the top section (one for each electrical phase) and three more in the bottom section. The breakers are in the front of the cabinet. There is an interior wall that separates the breaker compartment from the rear compartment where the connections are made. The rear of the cabinet was the area of interest as that is where the shipboard connections are made. The red panel on the side of the cabinet covers an opening that typically allows the horizontal bus bars for the three phases to connect to adjacent cabinets. There could be as many as four cabinets side by side in a single unit. The black electrical cables at the bottom of the cabinet are the test cables that bring the current in and out of the test box.

The rear cover panel would ordinarily be two louvered sections (one for the top and one for the bottom). For this test, a solid cover panel was used. DRS had a fixture created that supported the IR window along the vertical centerline of the rear cover. The window was mounted in a plastic holder (gray in the figure) that slid up and down on aluminum rails on either side of the centerline. This allowed the window to be placed anywhere along that track. The black on either side of the window holder is a fabric curtain that covers the unused area in between the tracks. Retractors at the top and bottom roll the curtain in and out as the window is moved.

Because of the sliding mount structure to accommodate variable window placement, the rear of the window bezels were actually 1.625” out from the surface of the rear panel cover. In a production installation, these would be flush.

Though not particularly evident in the figure, there are actually discrete holes behind the black curtain. There are 8 holes approximately 6” in diameter spaced evenly in between the rails. Each hole has a sliding aluminum plate that can cover the hole when not in use. In the figure, one of these sliding plates has been retracted from behind the current position of the window. These holes actually make the curtain redundant for the purpose of these tests. DRS explained that the holes were put in when it was unclear if the curtain assembly would be ready in time. Both systems were used during these tests.

Two windows were tested. Each was mounted in its own holder, so they could be easily exchanged. Images could also be taken through the holes with no window in place.

Inside the cabinet there were three connections (one for each phase) across the bottom and three more across the top. There are three vertical bus bars (one for each phase) that would normally hold the connections for the horizontal bus bars taking the three phases between adjacent cabinets. These vertical bus bars would normally have an offset in them, but for this test, they were flat for simplicity of fabrication. DRS ran test cables to only one phase instead of each phase separately. As such, the connections were made in series.

Looking in at the rear of the cabinet, the phases would be labeled A B and C from left to right. The test cables came into the cabinet and were attached to Phase C (connection on the right) at the top. Current passed into the breaker in the front of the cabinet, then from the breaker back into the rear to the vertical bus bar on phase C on the right. This bus bar took the current to the breaker on the bottom on the right, from there it returned to the rear compartment on phase C at the bottom. As only one phase was connected, phase C was connected to phase B (center) across the bottom via a jumper (a piece of bus bar between C and B). Current then passed through the lower phase B breaker, through the vertical bus bar to the upper phase B breaker, from the upper B breaker through another jumper to phase A, down through the phase A upper breaker, vertical bus bar and lower phase A breaker. The return cables were connected to the lower phase A breaker.

The test used 3 Volts at 1100 Amps. This provided enough energy through the connections to raise the temperature to realistic levels, representative of an actual cabinet operating under load. DRS does have a thermal chamber in which the cabinet can be tested, but this was not used for this test and the ambient temperature of mid 20’s (degrees C) was used.

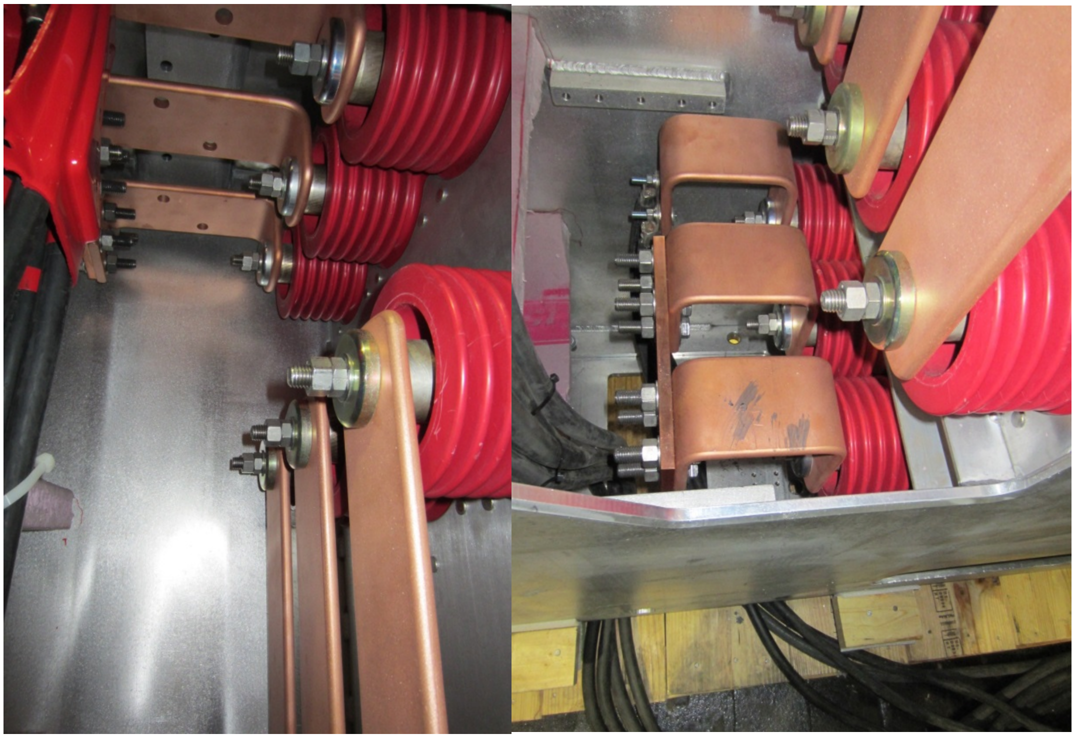

Figure 2 Cabinet Interior Upper Connections (L) and Lower Connections (R)

Figure 2 shows interior views of the cabinet through the side. The left photo shows the A, B and C connections in the upper portion of the cabinet at the top. Power connections are made to the C phase connection closest to the camera in the upper left. These connections are covered by the red rubber boot. A and B connections are at the top in the center and farthest away positions. The bus bar jumper that ties A to B is barely visible behind the rubber boot. In the bottom of the left photo, the three vertical bus bars that connect the top level breakers with the bottom level breakers can be seen.

On the right of the figure, the three phases in the bottom section are seen at the center of the photo. The cable connections are bolted to the A phase, which is the farthest from the camera. The bus bar jumper connecting phases B and C can be seen bolted to the other two bus bars. The three vertical bus bars between the breakers can be seen in the upper right of the photograph.

Some items that belong inside cabinet (voltage dividers) and some that were simulated (cable runs and cable brackets) were not present in tests or were not in their final positions and may represent additional line of sight obstructions to be dealt with.

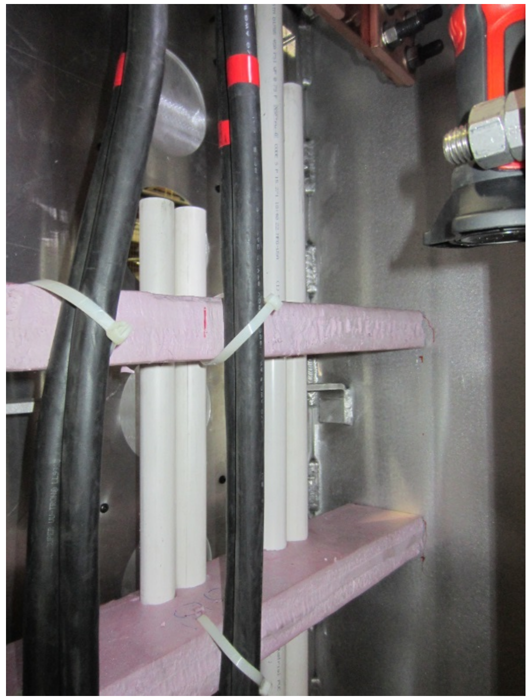

Figure 3 Interior of Rear of Cabinet as Viewed from the Side

Figure 3 is a view into the rear of the cabinet through the removable side cover. The connection cables going up to Phase C at the top of the cabinet can be seen at the left and center of the figure. As DRS only connected to one phase, the cables to the other two phases are represented by pieces of white PVC pipe of the approximate diameter. These can be seen in the center of the figure. The horizontal Styrofoam blocks represent the cable brackets that would be there with actual cables. These were included to simulate the locations of internal obstructions within the cabinet.

1.2 Windows and Fixturing

Two different windows were used for the testing, a four inch and a three inch crystal window. DRS had each window mounted in a rectangular plastic block. The block was made such that it could slide up and down in the aluminum tracks running up the rear of the cabinet. The window could be secured at any place on the tracks by means of fluted knobs. The ends of the upper and lower curtain rolls were secured to the sliding block, so that the curtain retracted or extended to cover the track as the window was moved. The hinged covers were left in place on the windows. For the first set of tests, only the four inch window was installed.

For the second set of tests, the curtains were removed from the window block and the holes with sliding covers were used instead. Also, the three inch window was installed above the four inch window on the tracks. This allowed both windows to be used in tests without stopping to exchange them in the tracks. With this arrangement, the four inch window could be placed at any of the 8 hole positions except the top one and the three inch could be placed anywhere except at the bottom hole.

Figure 4 shows a close up of the four inch window in its fixture on the rails. It is located at the next to the top position and the sliding cover has been retracted. The window cover has been hinged downward for viewing. The PVC pipe representing internal cables can be seen through the window.

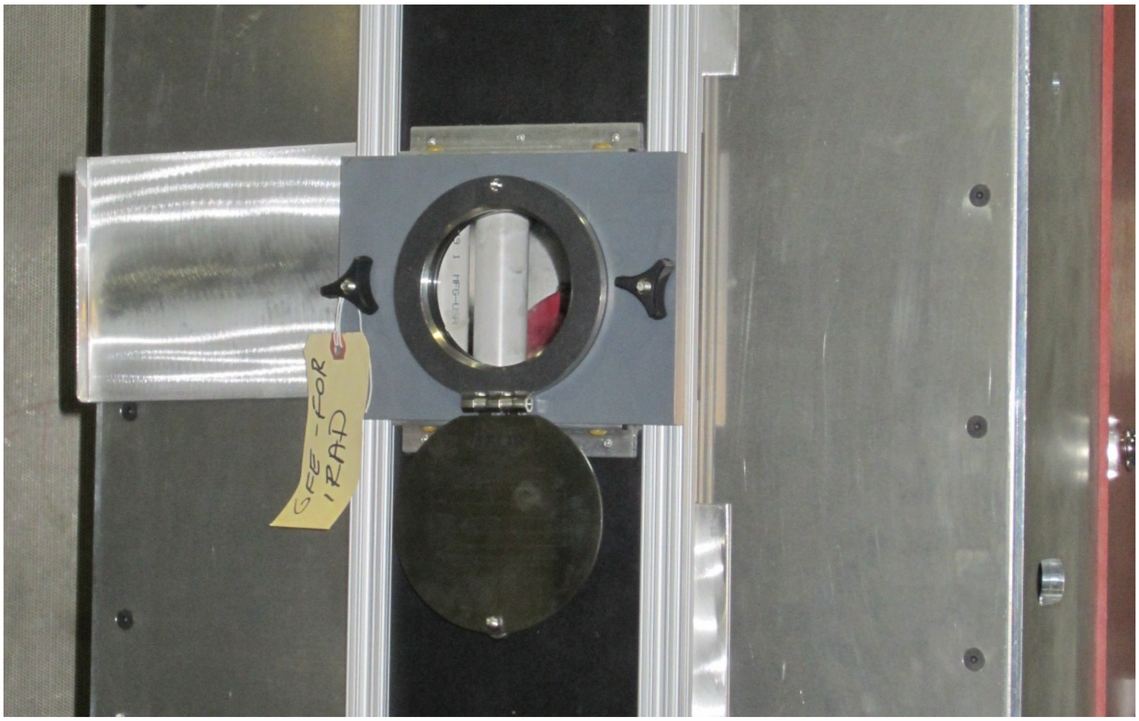

Figure 4 Close up of 4" Window Fixture

1.2.1 FLIR IRW-4S

This is the same window that was used in the laboratory tests. It is a four inch crystal (Calcium Fluoride) window in a stainless steel housing. The actual viewing aperture is 89mm (3.5”) once the bezel is accounted for. The specifications for this window are the closest to the preliminary specification for the LHA-8 panel inspections.

1.2.2 FLIR IRW-3C

This is also a Calcium Fluoride crystal window, three inch size. The actual viewing aperture is 69 mm (2.71”). This window was loaned to the project by NSWC Philadelphia.

1.3 Cameras

For this testing, it was not possible to borrow the FLIR T440 camera that was used in the lab tests. Instead, SUPSHIPS Gulf Coast provided a FLIR T300 camera which is of a similar style and has a similar feature set to the T440. Ingalls supplied a Fluke TI10 camera. This is of the same style as the Fluke TI32 that they supplied for the lab tests, but with a different feature set. The TI10 camera was brought as it is the camera that Ingalls uses in production. Both cameras have a built in visible camera and the ability to store images on an SD card.

1.3.1 FLIR T300

Figure 5 FLIR T300 Infrared Camera

The FLIR model T300 (Figure 5) is comparable to the FLIR 400 series thermal cameras currently used by the Navy for thermographic inspections. It has both visible and IR cameras, a variety of settings to compensate for the testing conditions, including a setting for the transmissivity of the IR window, and the ability to store the images. It was established in the lab tests that the best measurement tool on the camera to use was the box. The box can be made any size and placed anywhere on the image and the camera will return the highest temperature noted within the area of the box. The T300 has the ability to put multiple boxes on the image (even overlapping) and will return the highest temperature in each box. Two boxes were used in most of these tests.

The visible camera lens and its accompanying lamp are offset approximately two inches from the center of the IR camera lens. This became an issue in some of the tests.

1.3.2 Fluke TI10

Figure 6 Fluke TI10 Infrared Camera

The Fluke model TI10 (Figure 6) was borrowed from Huntington Ingalls shipyard. It is of the same series of Fluke camera as the TI32 camera that Ingalls supplied for the laboratory tests, only it has a much reduced feature set. The TI10 has the emissivity permanently set at 0.95 with no adjustment. Similarly, there is no transmissivity setting for the TI10. The camera assumes it is looking through air at the target. The consequence of these two settings is that the temperatures measured by the Fluke TI10 camera are considerably lower than that recorded by the FLIR camera. The primary difference is that the Fluke camera does not compensate for the attenuation of the light as it passes through the window. Less light means the camera interprets it as a lower temperature. Relative temperature differences were evident in the imagery, but the measurements were not considered representative of the actual temperatures.

The Fluke camera has a built in digital camera but no lamp. The only options are to take just IR images or to take IR and visible images simultaneously and display or save them as Picture in Picture (PiP) with the smaller IR image at the center, surrounded by the visible image. This is meant to put the IR image in a visible context, but it was only partially successful due to the geometry of imaging through a 4 inch window opening. The visible field of view often caught more of the window bezel than the interior of the cabinet, and parallax at such short distance caused the two images to not align properly.

This camera also did not have options for making measurements at the camera itself. There was a cross hair, and the camera reported the temperature at the spot of the cross hair. It was not possible to note the temperature at two different locations in the same image. It was also not possible to move the location of the cross hair in the image. The camera had to be repositioned with the cross hair at a different part of the target if another measurement was to be taken. The camera does have the ability to store the images in Fluke's proprietary digital format. If this is done, then the image can be analyzed with Fluke's software and the temperature at any point in the image can be determined. As the imagery from this camera was intended just to supplement the FLIR camera imagery for this report, the images were stored in bitmap format and only the information that was available on the display screen was captured.

1.3.3 Fluke 572 IR Thermometer

Figure 7 Fluke IR Thermometer

This is not a camera, but a hand held infrared thermometer (see Figure 7). It has a digital readout of temperature and a laser pointer to provide feedback to the operator for pointing the device at the surface where the temperature is to be read. It has an adjustable emissivity setting but the setting was not recorded. This was used by the DRS test personnel to determine when the temperature inside the box had stabilized. Temperatures at the various connections and on the bus bars were noted as the tests were set up and when parameters changed.

1.4 Testing Summary

There was a written test plan, but it was modified on site to fit the actual test setup and logistics. The order of the tests was changed to most efficiently utilize the conditions present in the DRS test facility.

The tests are:

Test A – Infrared thermography of normal (properly torqued) electrical connections through a 4" IR window. Connections with and without the rubber boot were examined.

Test B – Infrared thermography of a simulated fault (loosened connection) through a 4" IR window – no boot. This connection did not have the rubber boot.

Test C – Infrared thermography of a simulated fault (loosened connection) through a 4" IR window – with boot. The loosened connection was underneath the rubber boot.

Test D – Visible imaging through IR windows. Emphasis was on getting digital images to put the IR images in context.

Test E – Infrared imaging through a smaller 3" IR window. Thermal and visible images were taken.

Test F – Infrared imaging through 4" window, new boot configuration. Boot was repositioned.

Test G – Direct infrared imaging with no IR window in place. These images are as a reference to compare with the imagery through the IR windows.

Test H – Infrared imaging through IR windows with alternate dust boot. A second style of dust boot was jury rigged into place over the simulated faulty connections.

2 Test A – Thermography of Normal Electrical Connections through Window

This is a test of imaging "normal" connections through the IR windows; "normal" being a properly torqued, correct connection. As only a single phase was connected, there was one connection location on the bottom row and one on the top. The top row connection was covered by the rubber boot.

Figure 8 is a CAD drawing of the DRS prototype cabinet as viewed from the rear. It is annotated to note the areas where the images were taken and the windows were placed. The incoming cables were attached at Position B (shown in red) at the right top. There were actually 4 cables used rather than the two shown in the drawing. This was to carry the extra current used by the test setup. Two cables were bolted to the left most connection at Position B and two more cables were bolted at the right most connection at Position B. As mentioned above, a bus bar jumper was used between Position A and the phase connection to its left. The rubber boot was installed over the connections at Position B.

At the bottom of the figure, the exiting cables (also 4) are connected at Position C, two cables on the left most bolt and two cables on the right most bolt. A bus bar jumper connected Position D to the phase connection to its right. The cables to the top row were routed from the bottom of the cabinet as shown in the drawing, split apart so that one set of two ran up the outside edge of the cabinet and the other set of two ran between the two phases. The cables for the left phase and the center phase were represented by pieces of PVC pipe as noted above. They were placed so as to approximate the cables lying between the phases.

The IR windows were positioned differently for each test, in one of four positions. These positions corresponded approximately with the center of the holes cut in the rear panel. The positions are referenced by numbers in the drawing. The center positions were not used, as the primary connections of interest were those at the top and bottom of the cabinet, representing the connections made by the shipyard. In addition, the bus bars between cabinets were not installed, in the center of the cabinet, so there were no connections in that area to image.

Of primary interest in this test was the imaging of realistic connections and targets and the field of view through the IR windows. The limitations to field of view by the internal components and structures were also of importance.

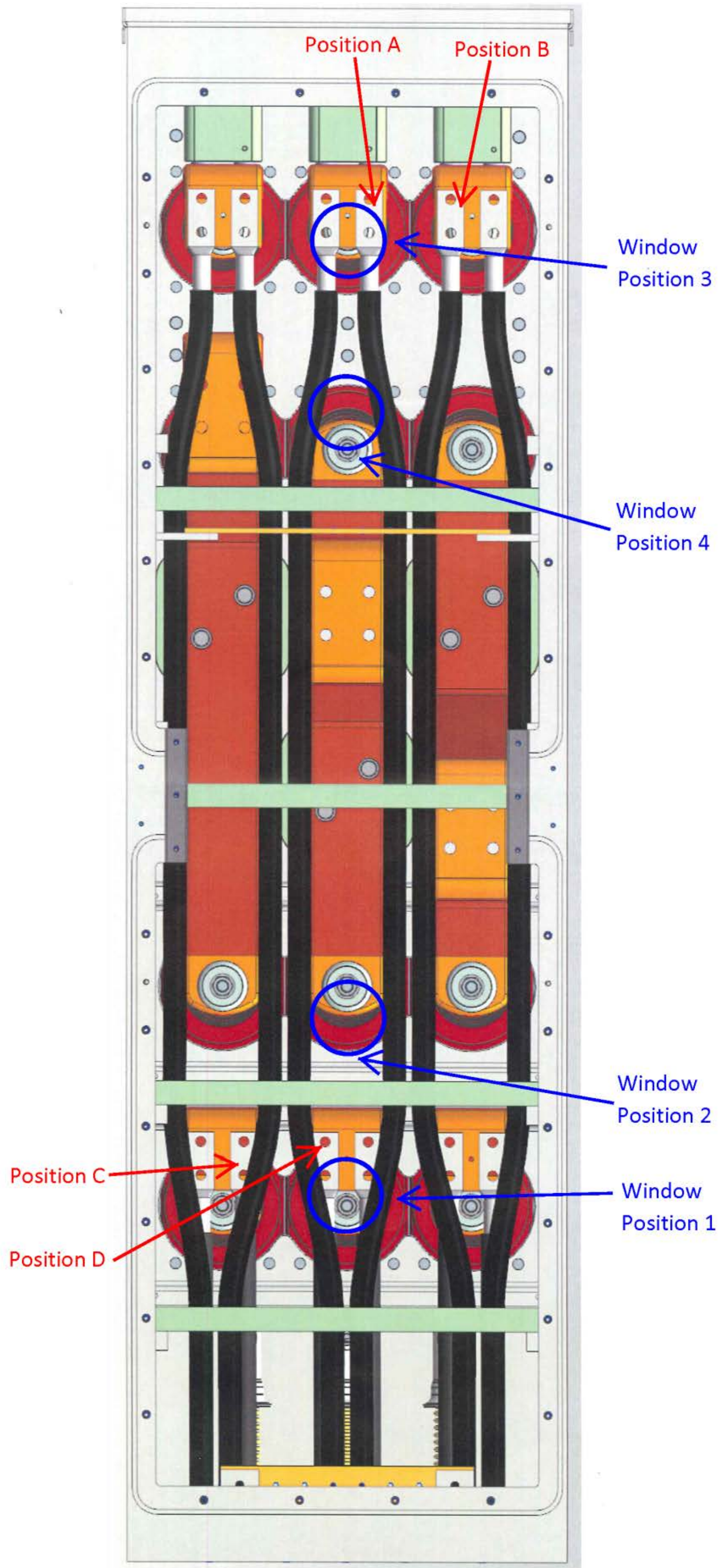

Figure 8 CAD Drawing of Rear of Prototype Cabinet

2.1 Test A Setup

For Test A, all connections were tightened down. The rubber boot was installed over position B. The rubber boot available for testing was not designed for this cabinet and consequently was not of the exact geometry needed to create a snug fit over the connection. For this test, the boot was installed with wire ties such that its upper half covered the connections, but its lower half covered the cables for about 6 inches below the bottom of the cable lugs. The shape of the boot also resulted in an air gap of nearly an inch between the bolt on the connection and the inner surface of the boot.

The four inch window was used for all images in Test A. It was variously positioned at all four of the window positions shown. The curtain over the window track (and the slides behind it) blocked all external light. The only light in the cabinet interior was from the viewing window itself.

The current was turned on in the test setup. Periodically, the side cover was removed from the cabinet and the Fluke 572 thermometer was used to check the connections and the bus bars. The reading stabilized at 41°C after about 1.5 hours. The side cover was replaced after each reading.

The FLIR camera was set for an emissivity of 0.8 (per Navy practices) and the transmissivity was set to 31%. This transmissivity setting was that used with this window during the laboratory tests. The FLIR camera was also set to use measurement boxes, where the temperature reported is the maximum temperature in the box. The boxes were repositioned as necessary for each reading to obtain the desired measurement.

The Fluke camera had no adjustments and consequently emissivity was fixed at 0.95 and transmissivity fixed at 100%. This will be evident when pictures are compared between the two cameras as the reported temperatures from the Fluke will be noticeably lower than those from the FLIR. The Fluke was set to take Picture in Picture (PiP) where the center of the picture is the IR image, surrounded by the digital visible image for context.

2.2 Test A Data

All thermal images shown in the report are from the FLIR T300 camera (FLIR logo appears in the lower left corner of the image) or the Fluke TI10 (shown as Picture in Picture with the IR image at the center and visible image surrounding it).

2.2.1 Images Taken From Window Position 1

The center of window position 1 is 19.25 inches from the bottom of the cabinet, approximately in line with the lower three phase connections to the cabinet. The window is at the center of the cabinet, when measured left to right.

Figure 9 shows a thermal image of Position C, the connections to Phase A on the bottom left of the cabinet. Both connection lugs can be seen in the image, with the measurement boxes surrounding both lugs (box 1) and the left most lug (box 2). The temperature difference shown is likely due to the actual differences in emissivity of the metal of the bolts and lugs, including any reflections. The dark areas to the left of and above the lugs are the PVC pipe used to simulate the cables going to the upper part of the cabinet. The right most PVC pipe was raised out of the picture since had it been a real cable, it would have been bent out of the way at this elevation as indicated in the drawing in Figure 8.

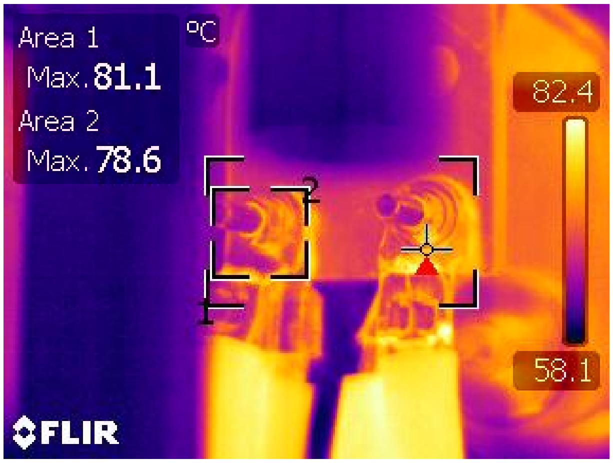

Figure 9 Position C as seen from Window Position 1

The horizontal angle of the camera to the perpendicular from the window in Figure 9 is approximately 25°.

Figure 10 shows a similar image but focused on the cables right below where the connections are made. With the emissivity of the cable jackets more uniform, the measured temperatures are closer together.

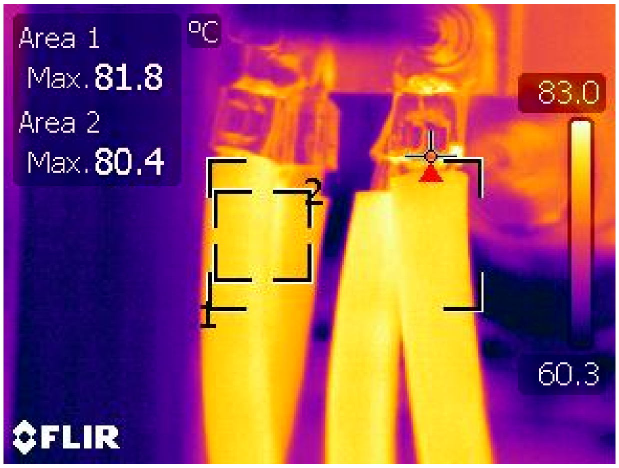

Figure 10 Cables at Position C from Window Position 1

Figure 11 shows an image that is viewing two phase connections at once. This shows the right most bolts at Phase A (position C) and Phase B (Position D) in the same image. This would allow comparison between adjacent phases. The temperature measurement shows a noticeable difference between the phases, but this is hard to judge in the prototype cabinet, since the connections at Position D are bolts through bus bar and at Position C they are through lugs. Each has slightly different emissivity.

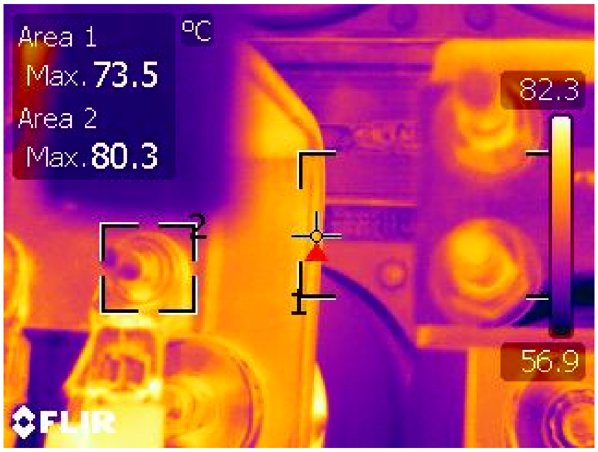

Figure 11 Bolts at Positions C and D from Window Position 1

The dark spot in the upper left is again the bottom of the PVC pipe in the cabinet.

Figure 12 shows an image from the Fluke camera of the same target.

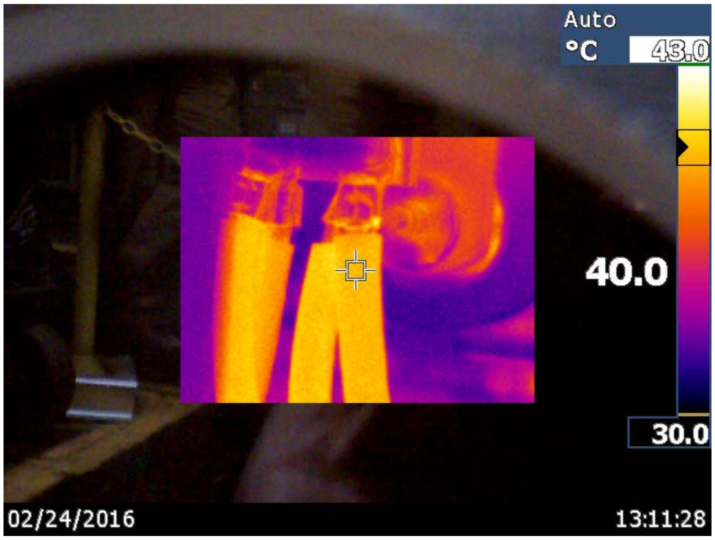

Figure 12 Fluke Image of Position C Cables from Window Position 1

Some of the limitations of this model camera can be seen in this image. The single measurement spot reads a temperature much lower than that of the FLIR camera because this camera cannot compensate for the transmissivity of the window. Also, the context meant to be provided by the surrounding digital image is not helpful. It shows the window bezel across the top of the image and the remaining items that can be seen in the image are reflections of items outside of the cabinet.

The next two figures show images taken from Window Position 1 but looking up at the connections to the vertical bus bars more in line with Window Position 2 as shown in Figure 8.

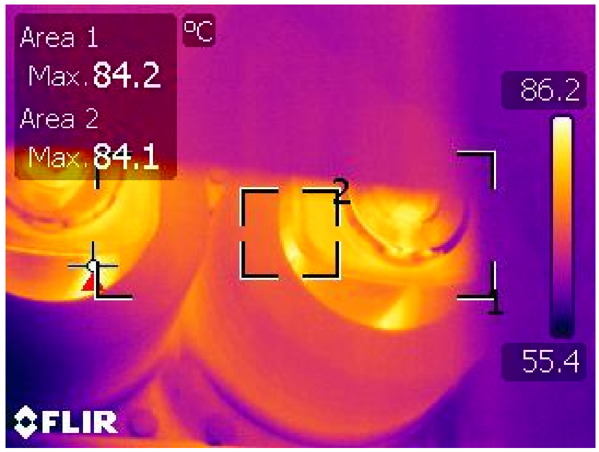

Figure 13 Center and Right Vertical Bus Bar Lower Connections

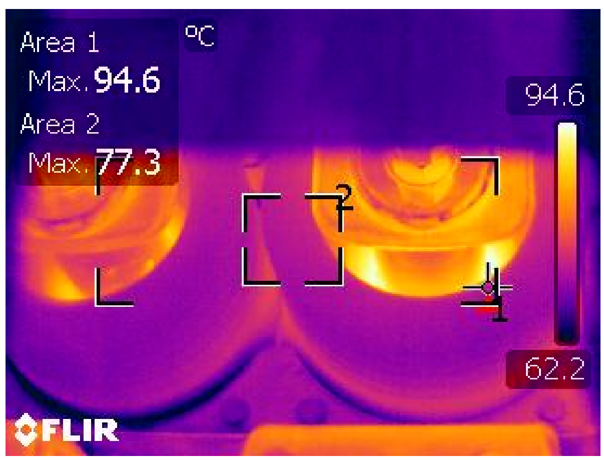

Figure 14 Left and Center Vertical Bus Bar Lower Connections

Figure 13 shows the lower ends of the center and right vertical bus bars. Figure 14 shows the left and center bus bars. These images show the field of view available (no attempt was made to set the temperature measurement boxes in the correct locations in the images). As these images were taken from about 11 inches below the targets, the vertical angle to the perpendicular from the window is about 54°. The darker band across the top of the images is the simulated bracket that holds the cables going up to the upper part of the cabinet. In this configuration, it is somewhat of an obstacle to viewing this level of connections from the window position below.

2.2.2 Images Taken From Window Position 2

The window was moved up to Position 2, which is 27.75" above the bottom of the cabinet and roughly in line with the lower end of the vertical bus bar connections, as shown above in Figure 8.

Figure 15 shows an image of the left and center vertical bus bar connections at the lower end.

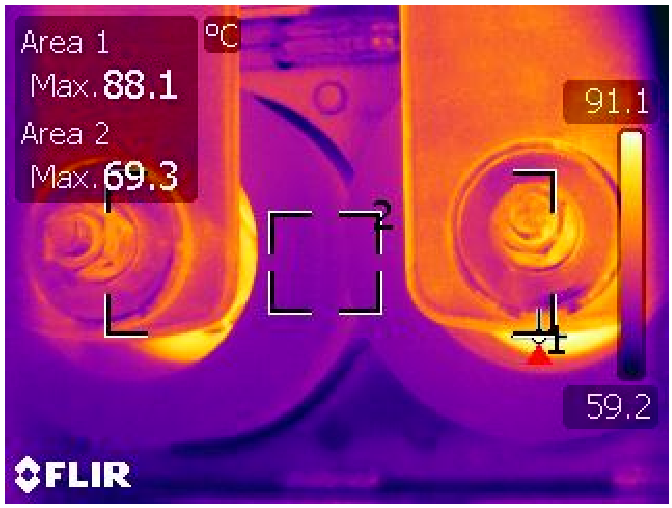

Figure 15 Lower Vertical Bus Bar Connections from Window Position 2

As expected, with the window approximately on the same level as the targets, the images are clear of obstructions. The PVC pipe representing the cables going to the cabinet above this level are close to the rear panel and out of the field of view of these images. Again, the temperature measurement boxes were not set in place.

Figure 16 shows the cables connected to the Phase A connection (Position C) as seen from Window Position 2.

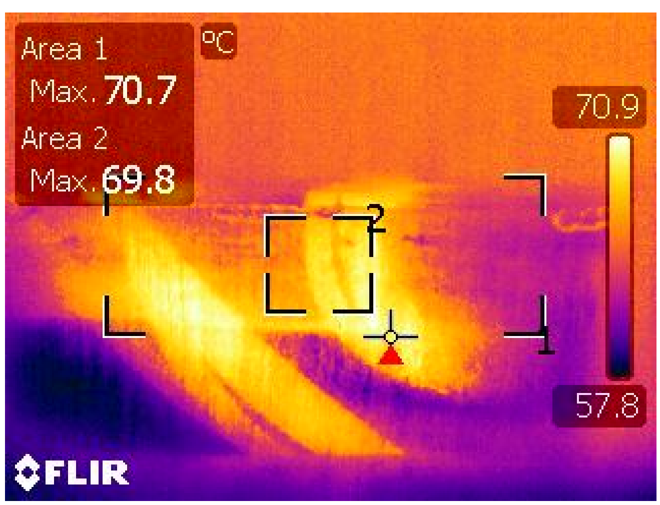

Figure 16 Cables at Position C as Seen From Window Position 2

This image is less successful. This is looking down from a higher window position onto the connections approximately 11 inches below. The cables can be seen, but not the cable lugs or bolts. This has some use since the cables do heat up, but it is difficult to determine how far away from the connections the camera is actually viewing. Some of the obscuration is from the simulated bracket that would hold the cables going to the top of the cabinet.

2.2.3 Images Taken From Window Position 3

The window was moved to Position 3, 68" above the bottom of the cabinet and approximately in line with the top row of connections, as shown above in Figure 8. The connections at Position B were covered by the rubber dust boot. The red rubber boot can be seen in Figure 17.

Figure 17 View of Rubber Dust Boot from Cabinet Side Opening

The view in the figure is from the cabinet side opening and is seeing the boot from the rear. The rubber dust boot completely covers the connections at Position B, both front and rear. The boot was not made for this geometry, so it was secured by wire ties. It also extends a considerable distance below the area where the connections are made. The point where the cables exit the bottom of the boot is at least 6 inches below where the cables terminate into lugs that are bolted to the bus bar. The boot was secured in this orientation at first since some openings in the boot corresponded with the shape of the bus bar. This boot has raised areas in the front and rear to accommodate the bolts that secure lugs or bus bars and these areas are not symmetrical. It is not particularly evident in the figure, but the higher of the raised areas is in the front in this orientation, toward the IR viewing window. This means that there is a larger air gap between the connection bolt and the inner surface of the boot in the front (toward the window) than there is in the rear.

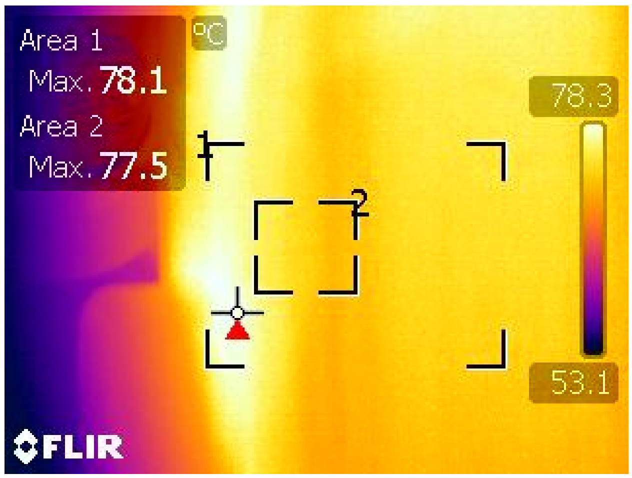

Figure 18 Dust Boot as Seen From Window Position 3

Figure 18 shows an IR image of the boot covering Position B from Window Position 3. It can be seen that there is a hotter spot along the edge of the boot material but it cannot be necessarily correlated with the connections underneath. The horizontal angle of the camera with the perpendicular to the window is about 32°.

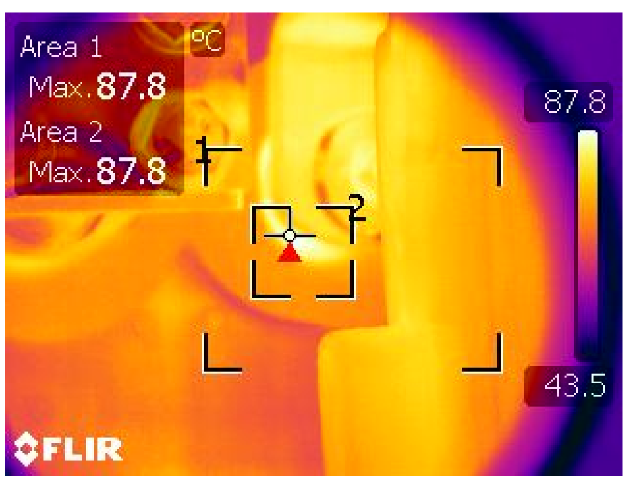

Figure 19 Bolts at Position A and Boot at Position B

Figure 19 puts the boot into some context. This image shows the bolts from Phase B at Position A in the upper left of the corner, partly obscured by the temperature readouts. The boot material fills the right side of the image up to the circular bezel of the window. Note that the bus bar and bolt visible just to the left of the boot and behind it in the picture is not the connection under the boot. This is the stationary connection of the Phase C bus bar to the breaker in the other compartment of the cabinet. The connections at Position B are completely covered by the boot. Figure 20 shows the same view with the Fluke camera.

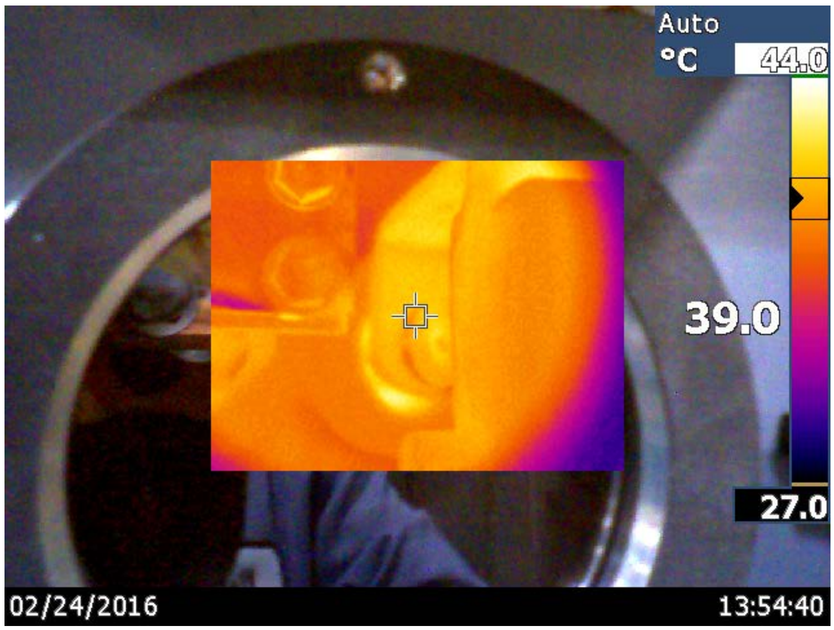

Figure 20 Bolts at Position A and Boot at Position B

At this position, there are no direct obstructions to viewing from the center window position. The cables from below, which were the principle obstruction, terminate in lugs connected at this level, so they are not in view.

2.2.4 Images Taken From Window Position 4

The window was moved to Window Position 4, which is 60 inches from the bottom of the cabinet and approximately in line with the top of the vertical bus bars as seen in the drawing in Figure 8 above. This position allows one to look up at the top row of connections.

Figure 21 shows an image of the bolts on Phase B at Position A and the boot covering Phase C at Position B. Both can be seen clearly but it is still difficult to get a viable temperature measurement from the boot. It should be noted that while the temperature at this point has been stable under the boot for around two hours, this boot was not made for this configuration and there are multiple locations around the edge of the boot where heat could escape.

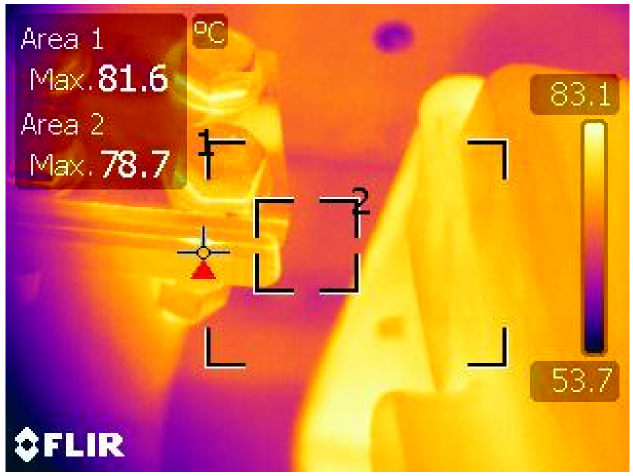

Figure 21 Positions A and B Viewed From Window Position 4

The vertical angle of the camera to the perpendicular of the window is about 48°.

2.3 Test A Summary

The purpose of Test A was to try viewing connections under normal circumstances through IR Windows at various positions. This was essentially a field of view test.

With the window in the center, there was no issue seeing connections to either side provided there was a line of sight view to the connection without obstruction. By pointing the camera at an angle, two phases of the connections could be captured in the same image, but not all three. To capture all three phase connections in the same image, the camera would need to be pulled back from the window a larger amount. The window would then not be large enough to see the entire scene given the natural field of view of the camera lens. Should this become an issue, it is possible to equip these cameras with a wide angle lens, which may permit this. Figure 22 illustrates this.

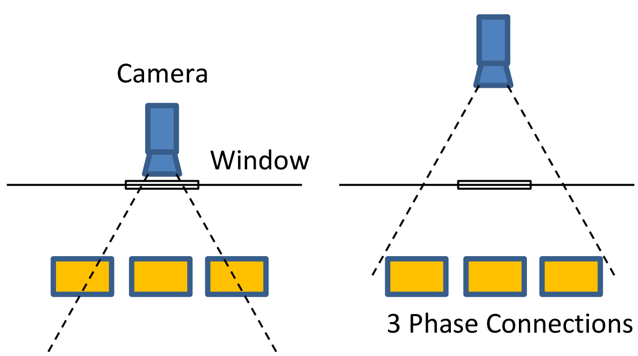

Figure 22 Camera Field of View vs. Window Size

Obstructions within the cabinet were the biggest issue with taking images. Cables (simulated or real) passing in front of other connections, as well as the brackets that held them would occasionally obscure the images. Imaging from a point in the rear panel cover above or below the connections was possible provided there were no internal obstructions.

With proper settings entered into the camera, relevant temperature measurements can be made through the IR windows. The difference between measurements from the FLIR and Fluke cameras illustrate how the camera must have the ability to correct for transmission loss through the window. The measurements from the Fluke camera are considerably lower than those from the FLIR.

The dust boot presents an obstruction to making measurements on the connections beneath it. The boot material is not transparent to IR radiation, so the heat would need to build up underneath the boot before the camera could register it. With the boot that was at hand for these tests, in this orientation, the boot was not snug to the connection (large air gap) and as the geometry did not match the bus bars inside the cabinet, there were multiple ways for the heat to escape under the boot. Alternatives to this boot placement were explored in subsequent tests.

3 Test B – Thermography of Fault Condition through Window – No Boot

For this test, a connection was loosened to simulate a fault. The loose lug formed a high impedance connection that got hotter than the normal connections when the current passed through it. For this test the connection was not under the rubber dust boot.

3.1 Test B Setup

The innermost connection at Position C was loosened. There are four cables connected at Position C. The left two are on the same bolt and that was left tight. The right two cables are also on one bolt and that one was loosened. Therefore it was expected that the connections on the right at Position C would be hotter than those on the left and also hotter than the bolts holding the jumper bus bar at Position D.

This test followed Test A. The current was turned off while the connection was loosened, but the system did not cool significantly during that time. Ten minutes after the current was turned back on, the temperature of the hot lug was 53°C as measured by the DRS Fluke 572 Thermometer. The remaining buses and connections read 45°C. The temperature stabilized at 61°C for the hot lug versus 46°C for the remaining lugs within another 15 minutes. The lugs were measured from the rear, since the side panel opening is the only access for these measurements.

Only one connection was loosened at a time for safety reasons. As the loose connection was on the bottom row, only the bottom two window positions were used. The four inch window was used in this test.

3.2 Test B Data

The window was placed at Position 1, 19.25 inches from the bottom of the cabinet and even with the row of connections that included the fault condition. Figure 23 shows the two connections at Position C.

Figure 23 Fault Condition at Position C Seen From Window Position 1

The connection on the right of the image was the one that was loosened. It can be seen from this image that the temperature is about 20°C higher than the tight connection on the left.

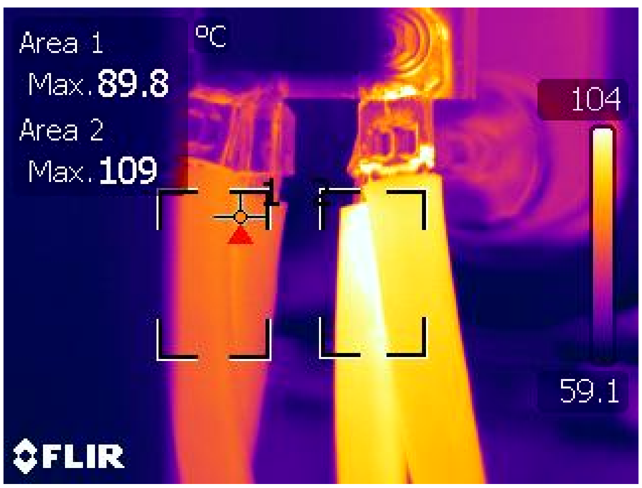

Figure 24 Cables beneath Position C with Loose Connection

In Figure 24, the camera measurement tools have been placed on the cables rather than the lugs. It can be seen that the loose connection on the right is hotter than the tight connection on the left, again by about 20°C. It is possible that the connection to the left is higher than normal due to the heat from the loose connection transferring along the bus bar at Position C.

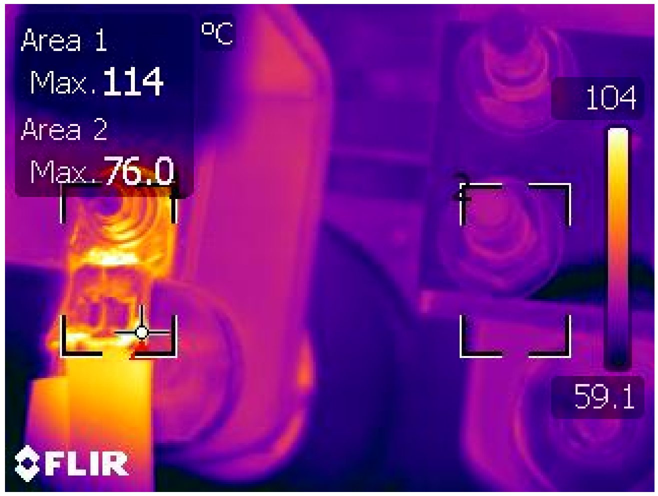

Figure 25 Loose Connection at Position C, and Connections at Position D

Figure 25 shows adjacent phase connections. The loose connection is at the left at Phase A (Position C) and the normal connection is at the bus bar jumper at position D. There is a 38°C difference in this measurement. This is typical of a field measurement detecting a fault. The difference between temperatures on adjacent phase connections is significant. As all three phase connections should be carrying the same current, their temperatures should be approximately the same. The large temperature difference indicates a fault.

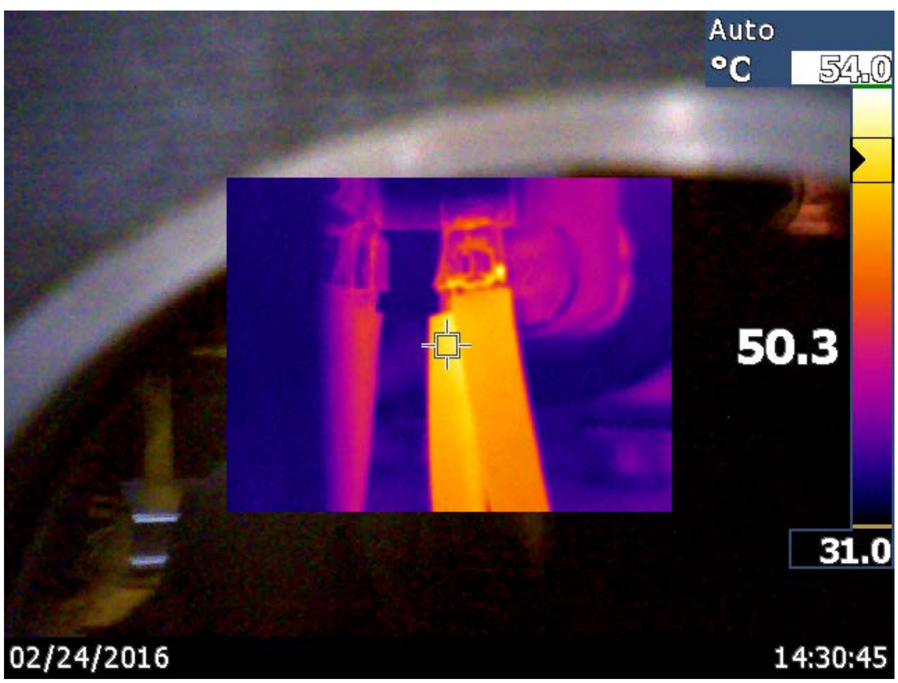

Figure 26 Loose Connection Position C with Fluke Camera

Figure 26 shows the same loose connection using the Fluke camera. Note the lower temperature measurement due to the camera not being able to compensate for the loss of transmission through the window. The temperature difference between the hot cable and the adjacent cooler cable is only 8°C, much lower than the 20°C seen by the compensated FLIR camera. The lower reported temperature difference would not look as severe as that reported by the FLIR camera.

The window was moved to Window Position 2 and the camera was directed down at Position C. As before, obstructions inside the cabinet prevented a clear view of the connections and the image was not usable.

3.3 Test B Summary

With no obstructions, it was possible to take an image that would result in detecting a faulty connection with the cabinet under load. The adjacent tight connection on the same bus bar was significantly cooler than the loose connection, as measured at the lugs and at the cables below the lugs. The adjacent phase connection was cooler yet, showing a more significant temperature difference. It is likely that the tight connection on the same bus bar as the fault was warmed by the heat from the faulty connection. The adjacent phase connection showed a larger temperature delta, as there was no opportunity for conductive heat to pass to that connection.

Where obstructions were present, as in imaging from a window position above the fault location, it was not possible to get a useful measurement. Also, this test was done without the rubber boot that will be installed over every connection in the cabinet, so this is more analogous to the thermographic inspections presently conducted on 450V panels. See Test C for data with the dust boot.

4 Test C – Thermography of Fault Condition through Window – Under Boot

For this test, a connection was loosened to simulate a fault. The loose lug formed a high impedance connection that got hotter than the normal connections when the current passed through it. The connection loosened in Test B at Phase A at the bottom of the cabinet was tightened to normal torque. For Test C, the connection under the rubber dust boot on Phase C at the top of the cabinet was loosened. Only one loose connection was used at a time for safety reasons.

4.1 Test C Setup

The innermost connection at Position B (upper section of cabinet, Phase C) was loosened. There are four cables connected at Position B. The right two are on the same bolt and that remained tight. The left two cables are also on one bolt and that one was loosened. Therefore it was expected that the connections on the left at Position C would be hotter than those on the right and also hotter than the bolts holding the jumper bus bar at Position A.

This test followed Test B. The current was turned off while the connection was loosened, but the system did not cool significantly during that time. The temperature stabilized for 30 minutes. The temperature at the hot lug was 62°C as measured by the DRS Fluke 572 Thermometer. The remaining buses and connections read 42°C. The temperature on the back side of the rubber boot was measured at 58°C. This side of the boot is tighter against the connections than the front side, which is viewed from the IR windows. These measurements were made from the rear, since the side panel opening is the only access for these measurements.

As the loose connection was on the bottom row, only the top two window positions were used. The four inch window was used in this test.

4.2 Test C Data

The window was first placed at Window Position 3, approximately in line with the three phase connections across the top of the cabinet. Figure 27 shows the bolt at Position A (Phase B) in the upper left just under the measurement readout and the dust boot at Position B covering the connections to Phase C. The measurement boxes show the temperature at this edge of the boot slightly higher than the bolt at Position A, but not significantly so. This is still the side of the boot that is farther away from the connection, with a larger air gap. This is very similar to the normal connections image (Figure 18), even though there is a simulated fault underneath the boot.

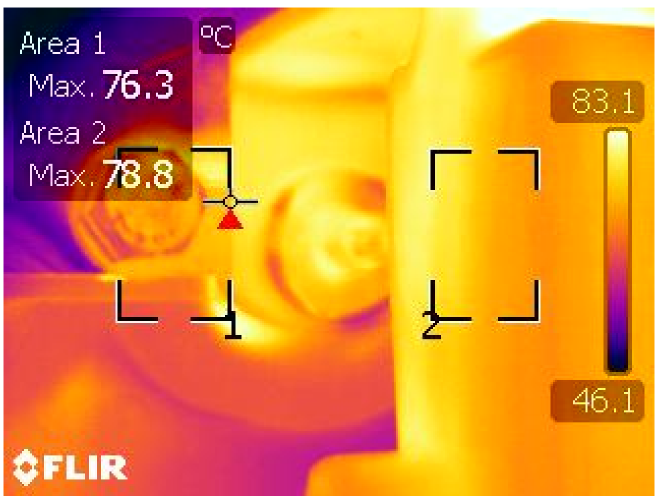

Figure 27 Bolt at Position A and Fault at Position B under Boot

Figure 28 shows an image of just the boot itself. While there is an elevated temperature, no hot spot is really evident.

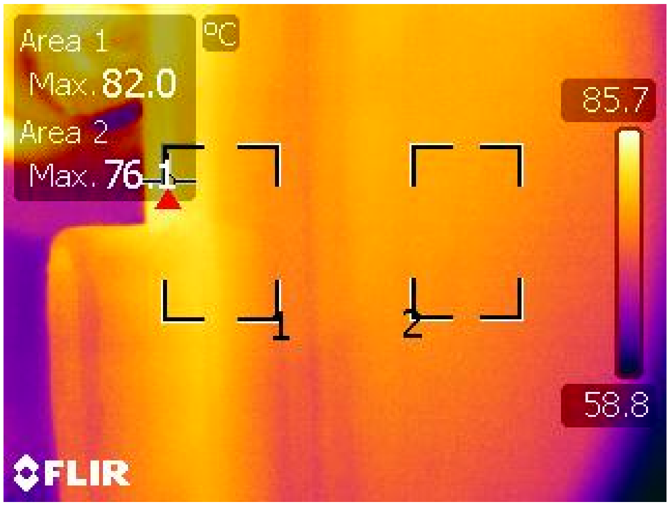

Figure 28 Boot at Position B, Fault under Boot

The window was moved to Position 4, eight inches below the connection row and looking up at the connections. This provided a view of where the cables exited below the boot.

Figure 29 shows the lower edge of the dust boot where the cables exit. It can be seen that there are hot spots on the boot material where the boot touches the hot cables as they exit. There is a temperature difference between the spot on the left (where the fault is) and the spot on the right. The actual difference is hard to quantify, as it is not known how much heat is being transferred through the boot material.

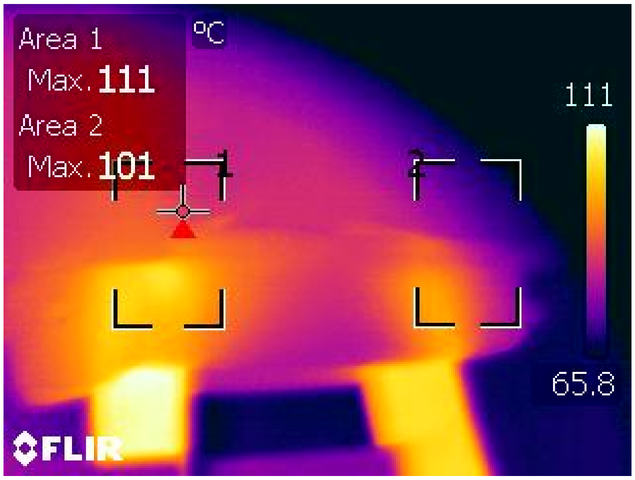

Figure 29 Lower Section of Boot and Cables Exiting

4.3 Test C Summary

The presence of the rubber dust boot does affect the measurements of the connections beneath. The boot material is not transparent to IR wavelengths, and so the measurement must rely on how much the boot material is heated by the hot connection beneath it. In this test, the boot material did not fit snug over the connection, as it was not made for the same geometry. Also, the boot design had a larger air gap on one side and this side was the one facing the IR window.

Where the air gap between the hot connection and the boot is small or they are actually touching, there is heat conducted to the outside surface of the boot. This heat is visible in the infrared images. While it is hard to rely on the absolute measurements in these cases, since the actual air gap and conduction properties of the material are not known, there are indications that some portions of the connections beneath the boot are hotter than others.

5 Test D – Visible Imaging through Windows

This test marked the second day of testing at the DRS facility. After review of the previous day's results and examination of the test setup, some changes were made in the order of the tests and in the setup so as to expedite the testing and ensure that all the tests could be completed in the allotted time.

The purpose of Test D was to examine taking visible images through the IR windows to be able to put the IR images in context. Previous laboratory tests indicated that an external light source with the camera can sometimes cause glare or reflections from the window, obscuring parts or all of the visible image. Without an external light source, there is insufficient light coming through the IR window around the IR camera lens to illuminate the interior of the cabinet and the visible images taken are too dark to be useful.

5.1 Test D Setup

For this and subsequent tests, the rolling curtain on either side of the window fixture on the rear panel of the cabinet was removed. It was still possible to position the window fixtures anywhere along the track that held them. The 8 movable slides at the different positions were used to close off the track when the window was positioned elsewhere, and could be individually slid open wherever the window was positioned.

To avoid having to disassemble the rack each time the window was switched, both windows were installed on the rack at the same time. The 3 inch window was slid in first. The 4 inch window was installed just below the 3 inch window. At the bottom of the cabinet, there is actually a position below Window Position 1 (see Figure 8). This allowed either the 3 inch window or the 4 inch window to be placed at Position 1 or Position 2. At the upper end of the cabinet, Window Position 3 is the highest position, so only the 3 inch window could be placed at Position 3. Either window could be placed at Window Position 4.

Figure 30 shows both windows installed and the curtain removed. Three inch window is above.

Figure 30 3 and 4 Inch Windows Installed

The connection at Position B (upper level, Phase C) was again loosened to simulate a fault. The rubber boot was repositioned for this and subsequent testing. The boot was reversed top to bottom and front to back.

Figure 31 shows the repositioned rubber boot over the loose connection at Position B.

Figure 31 Rubber Boot Repositioned over Upper Phase C Connections

In this orientation, the openings in the boot do not line up well with the bus bar and cable in the cabinet. Wire ties were used to hold the boot in place. There is more of a gap behind the boot, which allows some heat to escape, but in the front, the boot is much tighter to the connections. The side of the boot facing front in the photograph is the shallower side, so it is practically touching (or possibly actually touching) the bolt where the loose connection is located.

Also, the boot is now positioned so that the bottom of the boot is only about one inch below the connection lugs on the end of the cables. As before, the loose connection is the one on the left as viewed here and the connection on the right remained tight. No connections were loosened at the bottom of the cabinet. Based on the thermal images of the cables taken the previous day, it was determined to include more images of the cables as they exit the boot. With the boot in this position, the visible parts of the cables are much closer to the connections and will be more indicative of the temperatures at the actual connection points.

Both cameras have a built in digital camera for taking visible images. The FLIR camera takes a separate visible picture at the same time as the infrared picture, so they are of the same scene, allowing for parallax between the two lenses. The Fluke camera also takes a visible image at the same time as the infrared, but they are presented as Picture in Picture (PiP) with the IR picture in the center. At the close ranges to the subjects, this method suffers from parallax and the contextual visible image surrounding the IR image often captures the bezel of the window or the rear panel itself. The FLIR visible camera has a built in lamp that can be turned on and off. The Fluke camera does not have its own lamp.

Though the purpose of this test was to take visible images, most of the time the camera was placed in the best position for the infrared image, as the purpose of the images is to take temperature measurements. This often resulted in the visible camera lens in a bad position for imaging inside the cabinet, particularly with the smaller window. Sometimes the camera was repositioned to take another image so a useful visible image could be taken of the inside of the cabinet.

Three light sources were used. One was the built in lamp in the FLIR camera. The second was a Mini-Maglite® type flashlight, held adjacent to the camera in the IR window or held at another window or opening. The third was an LED shop light that was held at the other window in an attempt to illuminate the entire cabinet.

5.2 Test D Data

The window was placed at Window Position 1 (19.25” from bottom of cabinet) and visible images were taken of the bottom row of connections. With the camera lamp turned off and no other illumination, the image of the interior of the cabinet was dark and not useful.

The camera lamp was turned on. Figure 32 shows a visible image of the cables and lugs at Position C and the bolts and bus bar at Position D.

Figure 32 Visible image of Position C and Position D, Camera Lamp On

While it is possible to make out details inside the cabinet in the area of interest, there is also a reflection of the camera lamp from the window that obscures part of the connection area toward the right.

Figure 33 shows the same scene from the same window. In this image, the camera lamp was turned off and a secondary light source (flashlight) was held against the window adjacent to the camera lens.

Figure 33 Positions C and D, Camera Lamp Off, Secondary Illumination

Some slight reflection from the window can be seen at the lower left, which is outside of the area of interest. The majority of the reflections off the window have been eliminated. The reflections remaining in the image are coming from components inside the cabinet, namely the PVC pipe.

Figure 34 again shows the same scene, but with illumination from above.

Figure 34 Positions C and D, Secondary Illumination from Above

In this image, the camera lamp was again off, but the flashlight was held in Window Position 2, shining down onto the area of interest. There is considerable reflection off of the white PVC pipe, which would not be installed in an actual cabinet. This does show that a properly placed light source in a different window or opening can illuminate the area of interest.

Finally, the smaller window was placed at Window Position 3 (60” from bottom) while the larger window was kept at Position 1. This simulates a possible installation where there is just one window in the top half of the cabinet and one window in the bottom half of the cabinet. The camera was placed in the bottom window to image Positions C and D as in the last three tests. An LED shop light was held at the upper window to try to illuminate the interior of the cabinet.

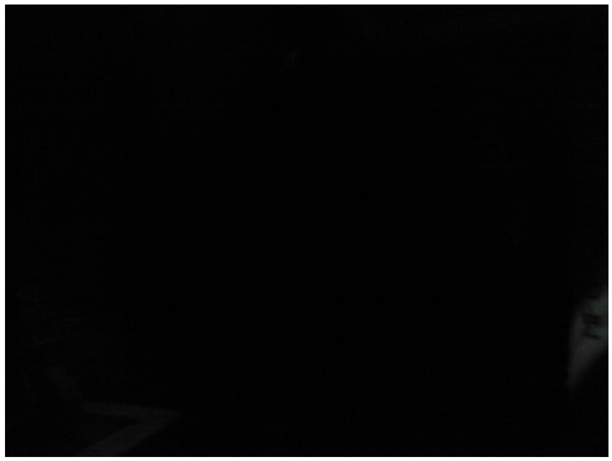

Figure 35 Image from Window Position 1 with light at Position 3

Figure 35 shows the result. The lamp was not powerful enough to illuminate the bottom of the cabinet from a small opening at the top of the cabinet. Or, there were too many obstructions in between the light and the area being imaged. A stronger lamp was not tried, but there are considerable internal obstructions that would make it unlikely that a brighter lamp would make a significant difference.

Imaging was now performed through the three inch window at Window Position 3 (top position). Figure 36 shows a visible image through the three inch window of the bolts and bus bar at Position A and a bit of the dust boot covering the connections at Position B.

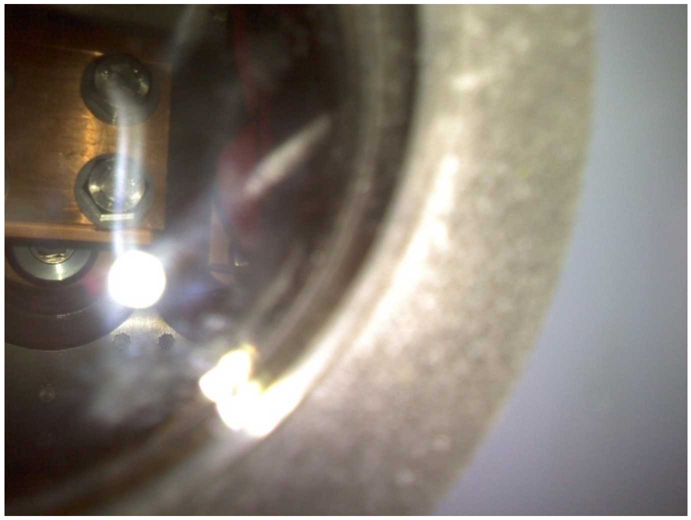

Figure 36 Positions A and B through 3 Inch Window

This illustrates one issue with the three inch window. The camera was aimed for the best view for the infrared image. On this camera and similar models, the center of the visible image lens is offset from the center of the IR lens by about two inches. It can be seen in the above image that the visible camera captured most of the window bezel and panel cover outside of the window. Again, the reflection from the camera lamp affects the image.

The next image (Figure 37) is the same view as in Figure 36, except that the visible image was used to line up the camera. It can be seen that the area of interest is much better framed. However, in this image, no consideration was given to the framing of the infrared image. For this smaller three inch window, it is better to take separate IR and visible images to make sure the camera angles and image framing are optimized. The camera lamp was on and again reflection can be seen off of the window.

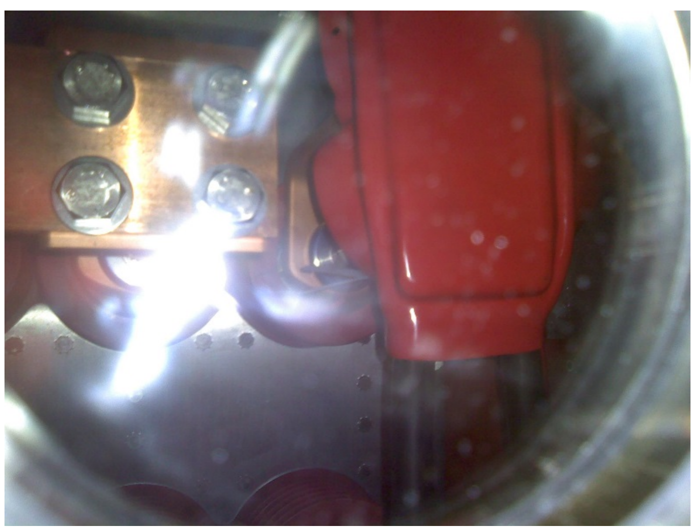

Figure 37 Visible Image Positions A & B from 3 Inch Window

Figure 38 shows the same scene, but with the camera lamp turned off and the flashlight at Window position 4 (8 inches below and aiming up).

Figure 38 Positions A & B with Secondary Illumination

With the three inch window, the camera lens takes up most of the available space. The above image shows a workable use of another light source in another opening. This eliminates the reflection, but does allow some features to be in dimmer light and is sensitive to the exact aiming of the secondary light.

The four inch window was placed at Window Position 1 near the bottom of the cabinet while the three inch window was left at Window Position 3. The shop light was held at the four inch window below to try to illuminate the interior of the cabinet. As before, the images through the window above were dark and not usable.

5.3 Test D Summary

This test confirmed the laboratory testing on visible imaging.

- With no illumination, there is not enough light coming through the small window opening to permit a usable visible image.
- The camera lamp does illuminate the cabinet interior, but often there is a reflection from the window affecting the image.
- A secondary light source, such as a flashlight aimed through the same window as the camera lens, or from another nearby opening permits good visible pictures to be taken of the interior of the cabinet.

- Attempts to illuminate the cabinet interior by means of a light at one end while imaging through a window at the other end were not successful. There were too many internal obstructions and the light was not bright enough and did not illuminate the areas of interest.

Another issue became evident when imaging through the smaller three inch window. The offset between the visible camera lens and the infrared lens and the close proximity of the camera to the window caused the visible camera to capture more of the window bezel and cabinet exterior than the area of interest inside the cabinet. This was generally not as much of an issue with the larger 4 inch window.

6 Test E – Field of View through 3 Inch Window

Test D concentrated on taking visible images. This test examined the field of view through the three inch window for infrared imaging. As the loose connection remained under the dust boot at Position B in the upper row of connections, all of the images were of this area. The thermal images in previous tests indicated that a more reliable indication of faults might be obtained from imaging the cables as they exit the boot rather than the boot itself. Therefore some additional images were taken from the window position below the top row, where the view of the cables would be better.

6.1 Test E Setup

The camera imaged the connections at Position A (Phase B in the middle) and Position B (Phase C) on the right with the rubber dust boot covering the connections. The left bolt at Position B remained loosened so the two cables connected on the left of the bus bar would indicate a fault and the two cables on the right connection at the bus bar would be tightened as normal.

The rubber dust boot was secured in the new position as described in section 5.1 above. In this configuration, the boot is nearly or actually touching the loosened bolt head at the fault location and the boot material is touching the cables as they exit. In addition, the cables exit the boot about one inch lower than the bottom of the lugs at the ends of the cables where they are bolted to the bus bar. Therefore the visible part of the cable is closer to the heat source than it was in previous tests.

The three inch window was placed at Window Position 3 (topmost, in line with upper row of connections) and Window Position 4 (next position down from top).

As on the previous day's testing, the emissivity of the FLIR camera was set to 0.8 and the transmissivity set to 31 %. The Fluke camera is permanently set for emissivity at 0.95 and transmissivity at 100 %. As measured by the Fluke 572 thermometer, the bus lines stabilized at 44°C and the hot spot at 62°C.

6.2 Test E Data

The three inch window was first placed at the topmost position (Window Position 3). Figure 39 shows an image of one of the bolts at Position A (center) and the rubber boot at Position B (right).

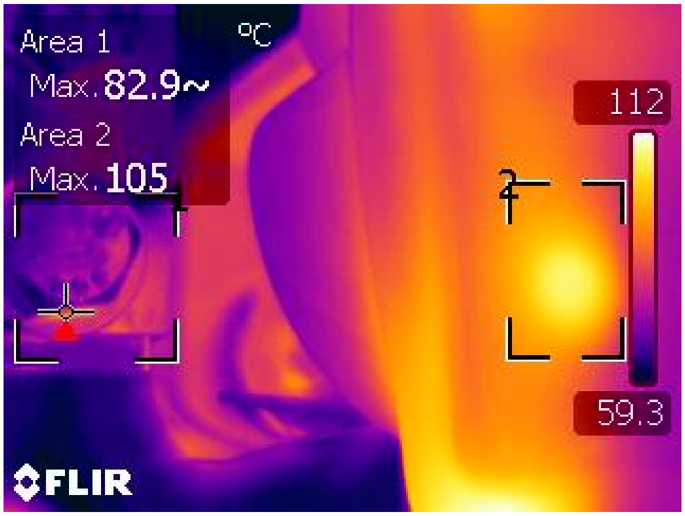

Figure 39 Positions A & B through 3 Inch Window

A hot spot can clearly be seen on the rubber boot where the loosened connection is located. The measurement shows a difference greater than 20°C between the tight connection at Position A and the hot spot on the boot at Position B. This does not represent a real test, as there would be a boot over both connections, but it does show that there is a definite difference where there is a loose connection.

The camera was then aimed at the cables as they exit below the boot. Figure 40 shows the two sets of cables.

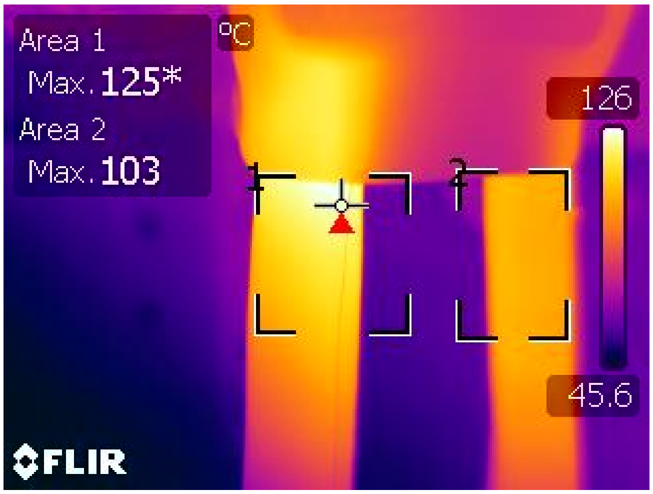

Figure 40 Cables below Boot at Position B

This image shows a temperature difference between the cables of 22°C. The cable on the left is noticeably hotter than the cable on the right, and the heat beneath the boot on the cable is also plain. In this particular case, the cable on the right is also being heated by conduction through the bus bar from the hottest spot under the loose connection on the left.

The window was repositioned to Window Position 4 (60" from bottom) so as to look up at the connections at Position B. This also provided a good view of the cables beneath the boot.

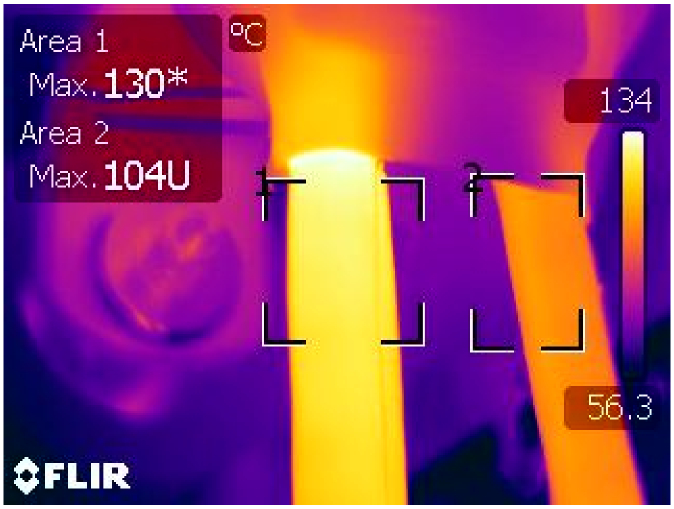

Figure 41 Cables below Boot Viewed From Below

Figure 41 shows and image of the cables just below the boot, as viewed from the lower window position, with similar results.

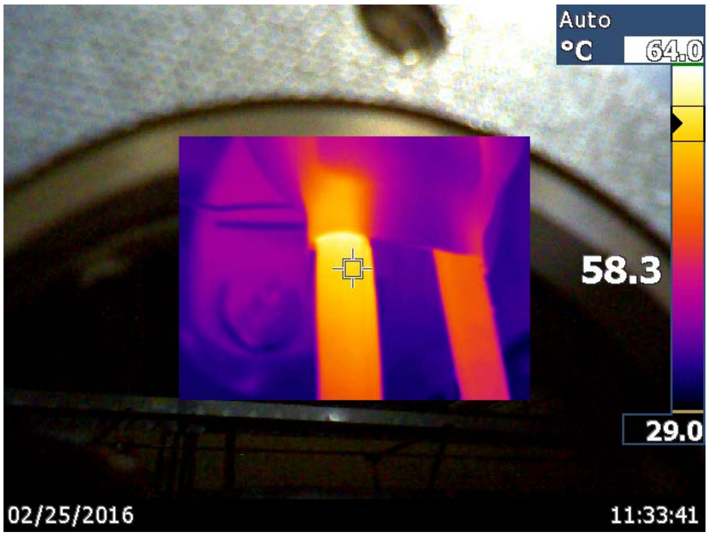

Figure 42 Fluke Camera Image of Cables below Boot

Figure 42 is an image from the Fluke camera through the three inch window at Window Position 4 (below the connections).

6.3 Test E Summary

The field of view of the three inch window is sufficient to take images of adjacent phases in this representative 4160V cabinet.

Two difficulties do arise with the three inch window. The first was noted in Test D regarding the visible imaging. If it is desired to take a visible image at the same time as the IR image to maintain context, then the offset between the lenses on the camera often results in the visible image being predominantly of the window bezel or outside the panel. A second image can always be taken after resetting the camera to view the visible image, but this adds an extra step to the process.

The second is more subtle and less of an issue. With the FLIR camera, it was useful to set two measurement boxes in the image, so that one box could be put over the connection on one phase and the other box over the connection on the adjacent phase. Using the larger four inch window, these boxes could be set in certain positions and used for multiple images within the cabinet. There was enough area in the window to permit the boxes to be placed over the areas of interest by just aiming the camera. With the smaller three inch window, there was more restriction on the camera placement and angle to get the desired areas of interest into the frame at the same time. This often required repositioning the boxes for each image. This can be done, but does add an extra step to the inspection. However, if instead of using the measurement boxes saved with the image, the images are examined in post processing and software is employed that is able to determine temperature at every point in the image, this is not a factor.

As seen in previous tests, there appears to be more consistency when viewing the cables as they exit under the boot rather than trying to measure hot spots on the boot. However, with the tighter boot position, hot spots are more evident. This may argue for placing the IR windows for a better view of the cables rather than the connections themselves.

7 Test F – Four Inch Window, Boot Repositioned

With the dust boot repositioned in a new configuration, Test C (see section 4) was repeated so that examining the loose connection under the boot could be done with the four inch window.

7.1 Test F Setup

The three inch window was positioned above the four inch window, so the highest position for the four inch window was Window Position 4 (60” above cabinet bottom). From this window, the camera would be looking up at the connections at Positions A and B.

7.2 Test F Data

Figure 43 shows the bolt at Phase B (Position A) and the hotspot on the boot where the loose connection is at Phase C (Position B). This is looking up at the connections from the window placed below, but the hot spot on the boot and the temperature difference are evident.

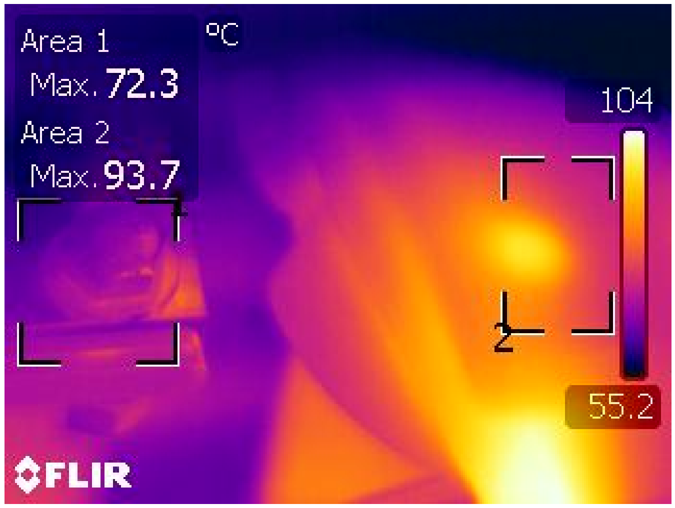

Figure 43 Positions A & B from 4 inch Window at Position 4

Figure 44 Cables below Position B through 4 Inch Window

Figure 44 shows the cables beneath the boot with a clear difference (> 20°C) between the cable with the loose connection and the cable with the tight connection.

7.3 Test F Summary

It can be seen in Test C above that with the boot in a configuration that allows a larger air gap, the loose connection beneath the boot does not produce a noticeable difference in the temperature on the outside of the boot. With the tighter boot configuration in Test F, the hotspot on the boot over the loose connection is evident. It still remained hard to determine a confidence level in the temperature measurement taken off the surface of the boot because the air gap and thermal transfer properties of the boot material were unknown. Also, the jury rigged nature of attaching this boot to the bus bar allowed heat to escape from multiple locations.

The imaging of the cables beneath the boot also showed promise in Test F, since the visible parts of the cables below the boot were much closer to the heat source of the loose connection than they were in Test C. The cable insulation also provides more uniformity of surface and in emissivity than the odd geometry of the boot or the reflective surface and multiple angles of the bolts and lugs without the boot.

Imaging cables below the boots looks to be a viable method of determining faults, but procedures will need to be developed that account for heat loss between the actual hotspot at the loose connection and the part of the cable that is visible.

8 Test G – Direct Imaging Reference – No Windows

Using the sliding panels in the DRS test setup, it was possible to take images with no window in place. The windows could be positioned out of the way and the sliding panel opened up for a direct view inside the cabinet. This would not be permitted in an actual cabinet, but it does provide the opportunity for comparison of imaging through windows with direct imaging as is now done in the 450V panels.

8.1 Test G Setup

The windows were both moved to positions in the middle of the cabinet, out of the way of the areas of interest. Images were taken through the openings left after the sliding panels were moved out of the ways. These openings were approximately 6 inches in diameter (larger than the windows) and afforded the ability to place the camera in the optimum position and angle and to use the camera lamp for the visible images.

Images were taken of Position C and Position D in the bottom row of connections through the opening at Window Position 1 (bottommost). Images were also taken of Position A and Position B in the top row of connections through the opening at Window Position 3 (topmost). The loose connection simulating a fault was still under the boot at Position B.

With no window, the FLIR camera was set for emissivity = 0.8 and transmissivity at 100 %. The Fluke camera remained at emissivity = 0.95 and transmissivity at 100 %.

8.2 Test G Data

The camera was first placed in the opening at Window Position 1 (19.25” above cabinet bottom) and images were taken at Position C and Position D.

Figure 45 and Figure 46 below show the connections at Position C and the bolts on bus bar at Position D in two images taken at the same time. The visible image is a wider field of view, but puts the IR image in context. The camera lamp was on for the visible image.

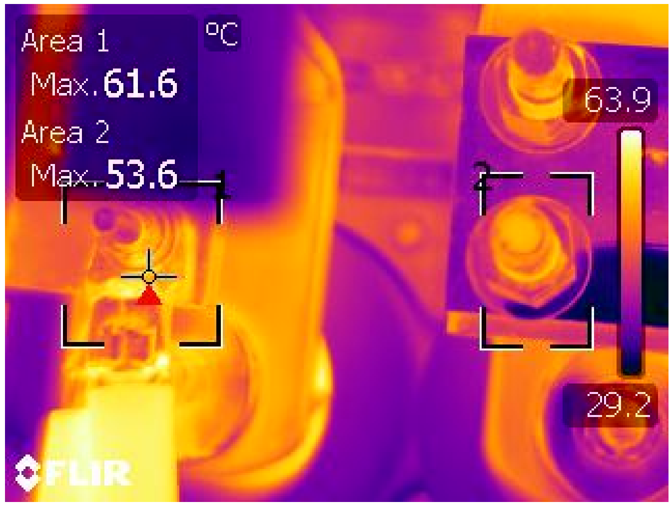

Figure 45 Positions C and D with No Window

Figure 46 Visible Image of Positions C and D with No Window

Aside from the lack of reflection from the camera lamp in the visible image, these images are very similar to those taken through the windows.

Figure 47 shows the cables below Position C through the opening at Window Position 1. The measurements on the two cable sets are almost identical, as is expected since they are both tightened correctly.

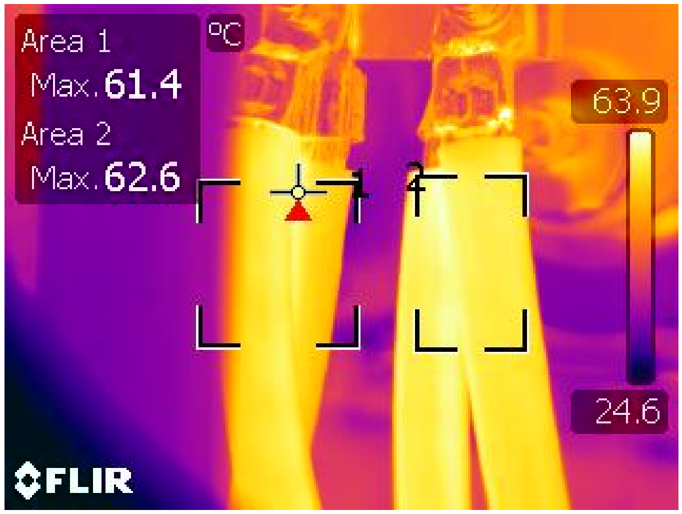

Figure 47 Cables below Position C, No Window

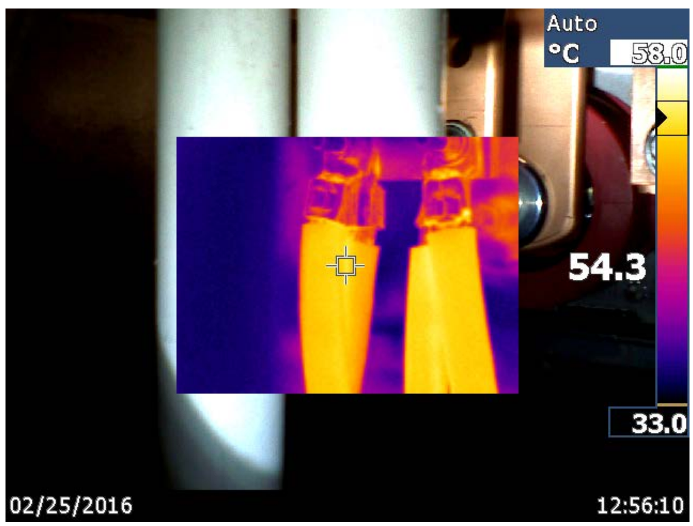

Figure 48 Fluke Camera Image of Cables at Position C, No Window

Figure 48 above shows the Fluke camera image of the same scene. A flashlight was held alongside the camera to illuminate the cabinet interior for the visible image. With the same transmissivity setting, the measured temperatures from the two cameras are much closer, the remaining differences due to the differing emissivity settings.

The camera was then moved to the opening at Window Position 3 to take images of the upper row of connections.

Figure 49 and Figure 50 were taken at the same time. The hotspot on the boot is measured against the bolt on the adjacent phase. The visible image shows both items in context. The camera lamp was on.

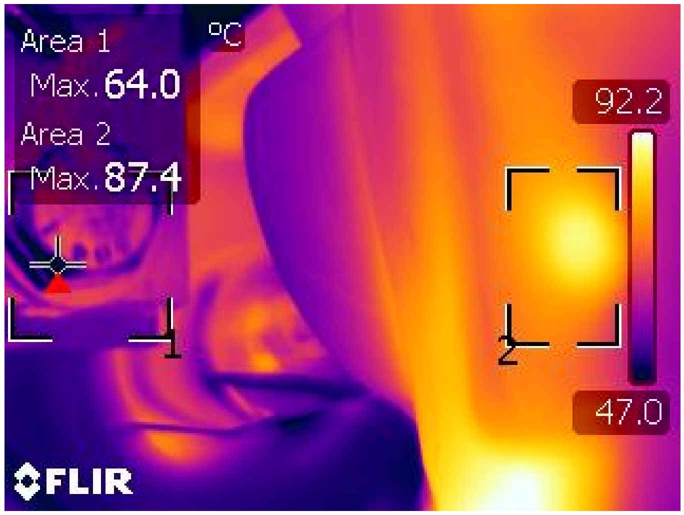

Figure 49 Positions A and B, No Window

Figure 50 Visible Image, Positions A and B, No Window

Figure 51 and Figure 52 below show the cables below the dust boot at Position B with the visible image taken at the same time for context. Again, these are similar to those taken through the window.

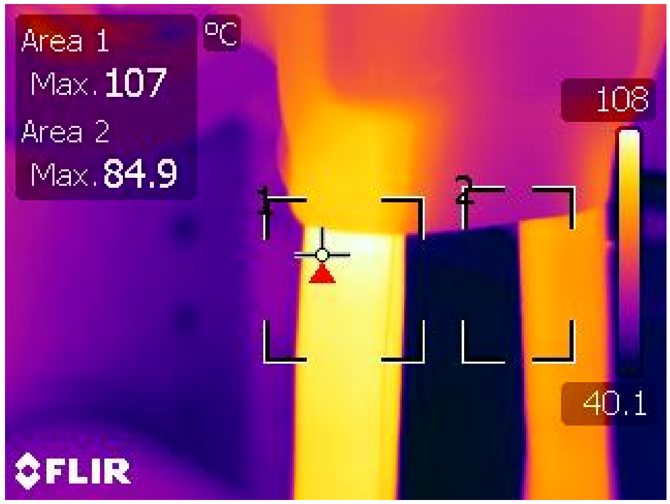

Figure 51 Cables below Position B, No Window

Figure 52 Visible Image, Cables below Position B, No Window

The larger opening with no window permitted more flexibility in getting the visible image properly framed. This is more evident in the picture of the same scene from the Fluke camera, as shown in Figure 53. With the larger opening, the visible image surrounding the IR image can be correctly placed to show context in the Picture in Picture view, mostly because the camera can be held further back from the face of the panel. This was difficult to achieve with the window in place.

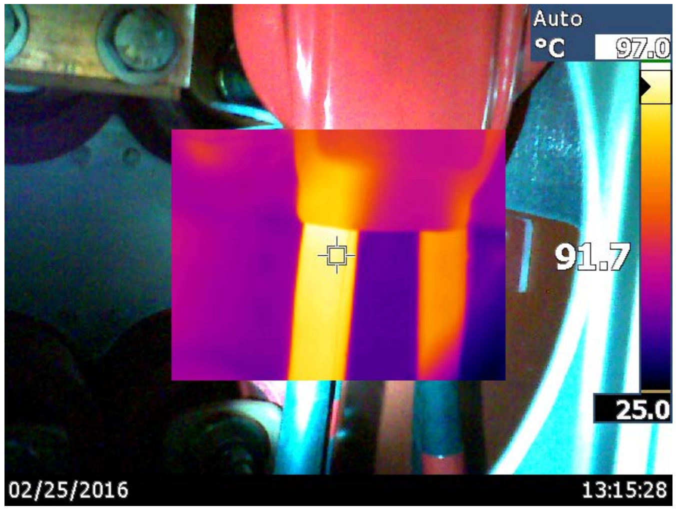

Figure 53 Fluke Camera, Cables below Position B, No Window

8.3 Test G Summary

The images in this test were taken as a reference against which the images through windows can be compared.

In general, the images through the windows are as useful as those without windows. Some factors regarding using the windows have already been noted above. The reduced field of view with the windows sometimes makes it more difficult to get a good corresponding visible image for context without reshooting the visible image separately. The lighting needed to illuminate inside the cabinet for visible images also has a problem with reflections when using windows.

The IR imaging through windows is about the same as without windows. The transmissivity setting of the camera comes into play when using windows. Due to the logistics of how the test setup was arranged, the No Window images and measurements were taken after the majority of the images with windows. An ideal way to calibrate the transmissivity setting of the camera is to take a measurement of an object without the window, then image it with the window and adjust the transmissivity setting until the measurement is the same as without the window. This was not possible due to the setup and time allotted for the testing. Therefore, the transmissivity setting used in the laboratory testing was used in these tests.

For a practical test, provided the transmissivity setting does not change between tests, it will not significantly affect the results as the tests are looking for differences in measurement between adjacent connections rather than the absolute temperatures. The transmissivity setting will affect both measurements the same and the difference will be preserved.

9 Test H – Imaging with Alternate Dust Boot

The red dust boot used in the testing to this point was obtained from another source and it did not match the geometry of the connection bus bars and cables in the DRS prototype cabinet. Therefore, it was jury rigged in place using wire ties. The actual composition of the red boot is unknown, but it is typical of a boot used in the industry.

DRS had a sample of a dust boot of a different material. This boot is used in other DRS cabinets for the same purpose. However, it was not the same geometry as what would be used in the 4160V cabinets. Therefore, it did not fit over the connections very well either. However, being a different material, it was decided that it should be tested. This boot was cut up and a portion of it wire tied over the loose connection at Position B, so as to have a comparison with the red boot.

9.1 Test H Setup

The test setup was shut down and the red dust boot was removed. The DRS semi-translucent boot material was fixed in place over the loose connection at Position B on the upper row. It was wire tied to lay as flat as possible and as close to the actual connections as possible. Again, there was about one inch of cable between the connection lugs at the end of the cable and the bottom edge of the boot material. Typically, the boot material is molded to a shape for each connection to allow it to be as snug as possible. This material was fixed in place to replicate that on the front side. On the rear side away from the window, there were gaps where heat could escape, but that was a consequence of fixing it fairly tight on the front.

Figure 54 shows the translucent DRS boot material fixed in place over the connections at Position B.

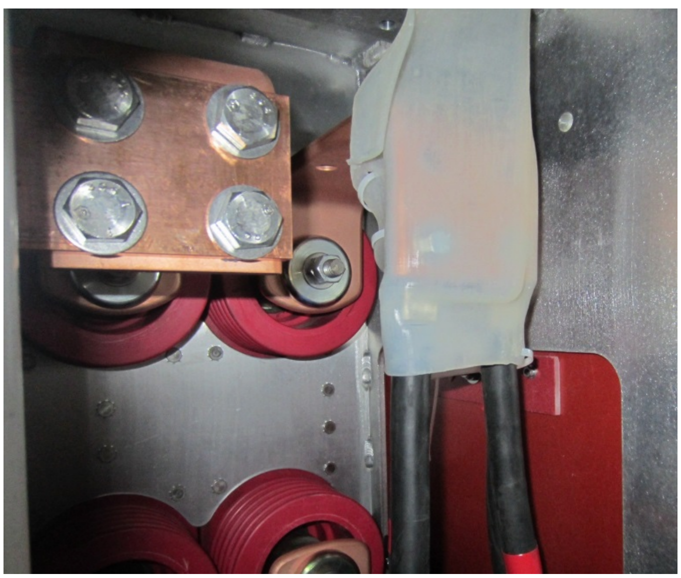

Figure 54 Alternate Boot Material over Position B

The material was fastened tight against the connections, reproducing the position of the red boot from Test F as close as possible. While translucent in the visible, this material was not transparent in the infrared. Therefore, the thermal camera was only able to read the surface temperature of the boot material.

The current in the test setup was only off long enough for the switching of the boot material. Power was restored and the temperature stabilized after one half hour at 42°C for the bus locations and 64°C for the hot connection, as measured with the Fluke 572 thermometer.

The FLIR camera settings were reset to emissivity = 0.8 and transmissivity = 31 %. Fluke camera settings remained at emissivity = 0.95 and transmissivity = 100 %.

The three inch window was placed in the uppermost position (Window Position 3).

9.2 Test H Data

Figure 55 shows the bolt head at Position A and the hot spot on the boot material over the loose connection at Position B.

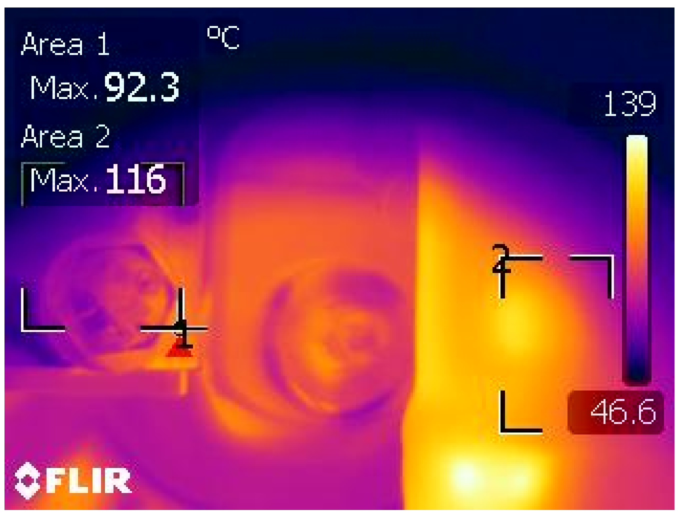

Figure 55 Positions A and B with Alternative Boot Material

While the actual temperature measured on the boot is not the temperature of the connection beneath, a definite hot spot is visible.

In the next image (Figure 56) the camera has been tilted to get the bolt at Position A and the cable below the boot material at Position B. There is a larger temperature difference here. However, in a practical examination in an actual cabinet, the cables between the two phases would be imaged.

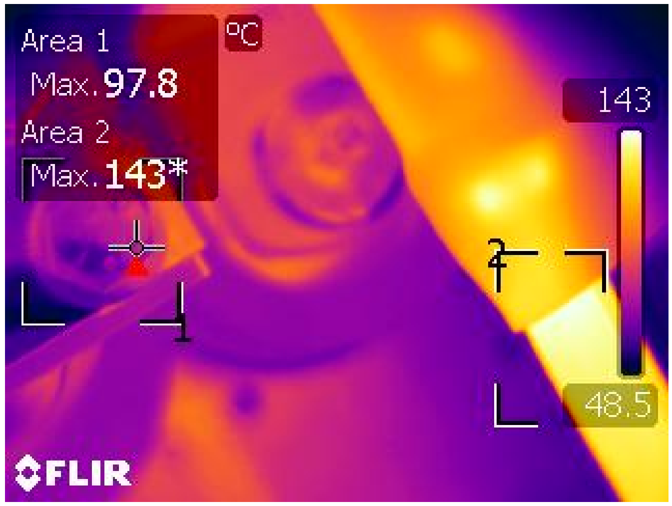

Figure 56 Position A and Cable below Position B, Alternate Boot Material

As seen with the other boot material, the cables below the boot may be a more reliable indication of a problem with the connection. In Figure 57 the temperature difference between the two cables is evident, even though the right cable is also being heated by the bad connection through the bus bar that they share.

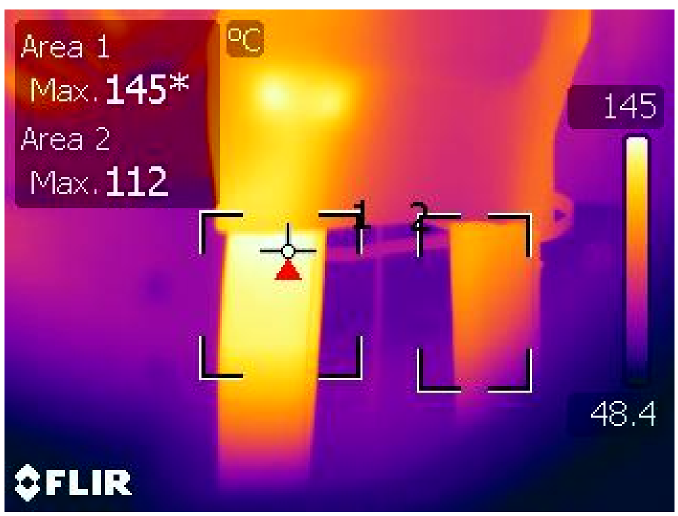

Figure 57 Cables below Alternate Boot at Position B

The next image might be more representative of what could be seen in a working completed cabinet. Figure 58 shows the measurement of the hot spot on the surface of the dust boot material, compared with the area adjacent to that where there is a connection, but that connection is not loose. The hot spot is actually over the crimp barrel of the lug at the end of the cable where it is touching the boot material. The crimp barrel of the lug on the right cable may also be touching, but it is not nearly as hot.

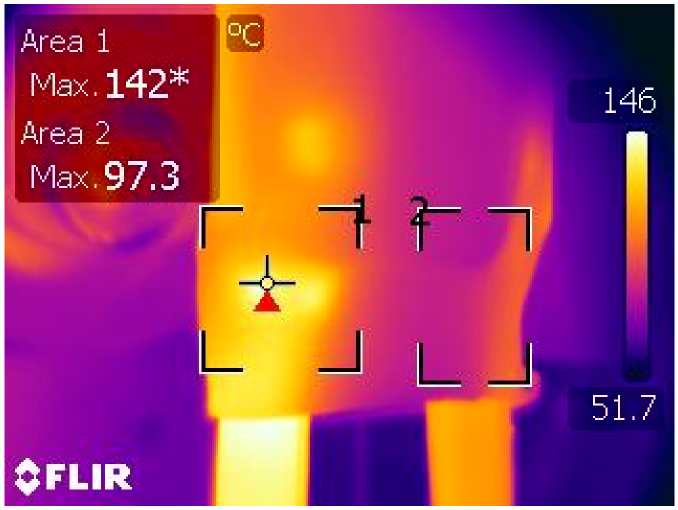

Figure 58 Alternate Boot Material, Hot Spot and Adjacent

In an actual cabinet, there would also be a boot over the adjacent phase connections, and so the good connection may look like the cable in the right of the image while the fault on the adjacent phase may look like the cable on the left in the image.

9.3 Test H Summary

While the alternate boot material was translucent in visible light and was somewhat thinner than the red boot used in previous tests, it was not transparent to infrared. The thermal imaging was therefore limited to the surface of the boot material. Where the hot loose connection or cable was close to or touching the boot material, a hot spot would appear on the surface of the boot. There is still a question of the accuracy of the temperature measurements due to the uncertainty of the heat transfer through the boot material, but the hot spot created by the loose connection is definitely evident in the imagery.

In this test, imaging the cables where they come out from under the boot may be the better option. The temperature of the cable will decrease the farther it is measured from the bad connection, but if this is kept to a minimum and kept consistent, the temperature differences between the cable with the loose connection and the cable with the normal connection are quite high.

10 Conclusions

The objective of this testing was to take thermal images through IR transparent windows of a relevant 4160V ship electrical cabinet. Using a cabinet mock-up in a factory testing facility allowed a safe simulation of faulty connections, which was the most interesting thing to test. Previous laboratory testing characterized the performance of the windows and revealed potential issues. This testing explored the practical issues with imaging inside a representative cabinet. The most significant things determined were:

8 Thermal imaging through windows in a panel can be done with proper attention paid to camera settings. Normal and faulty connections were imaged with faulty connections plainly evident by the higher heat produced across the connection compared to normal connections.

9 Thermal imaging through windows is fundamentally not much different than imaging through an open panel cover. However, adjustments to procedures will need to be made. The most significant issue is setting the camera to compensate for the attenuation of the light through the window. Other practical issues regarding how much can be imaged through the field of view and the need for supplemental illumination also need to be taken into account. New procedures will have to be developed for practical tests to account for these factors, including a new "star chart" for reference to severity of fault conditions. Some of the thermal imaging cameras have features that might be helpful when developing new procedures, such as multiple measurement areas, difference measurements, and annotated reports generated in the camera.

10 Internal obstructions are the biggest issue for imaging through windows. By angling the camera to the window, the field of view is sufficient to see anywhere in the cabinet from one window in the top and one in the bottom, were it not for internal obstructions. Cables running from the bottom to connections at the top and the brackets that hold them can obscure connections near the bottom. The nature of the bus bars (vertical between cabinet halves and horizontal between cabinets) mean that some connections will be obscured.

This will be a design challenge for the cabinet manufacturer, to minimize the number of internal obstructions and optimize the placement of the windows. It may be more advantageous to include more windows to provide better line of sight to all internal connections.

11 The dust boots that cover all connections within the 4160V cabinets definitely affect thermal imaging. Two dust boot materials were tested, but neither was designed for this particular cabinet. The existing boot materials are not transparent to infrared wavelengths. Therefore, detecting a faulty connection requires that the heat from the connection be transferred to the boot, and then the hot spot on the boot surface can be measured.

In this case, proper fit and location of the dust boot makes a difference. The more air gap there is between the connection and the boot surface, the less heat gets transferred. The most evident hot spots in the thermal images were where the boot material was very close or touching the hot connection. Design of new boot covers that are transparent to IR wavelengths is an area worth further investigation.

12 Alternately, given that it will be hard to tell how much heat is being transferred to the boot material, it may be better to image the cables as they enter or exit beneath the dust boot. The cables have a more uniform emissivity than the connections themselves. The dust boots can be designed so that the cables exit from the boot not far from where the cable lug is bolted to the bus bar. These tests show that the cable to a faulty connection is considerably hotter than adjacent cables with good connections and well evident in the thermal images. Some additional research would need to be completed to determine the amount of temperature loss down the

cable, so as to get reliable temperature measurements and redefining the criteria in the “star charts”. If this method is chosen, then it would be better to select window locations in the panel cover that afford view of the cables rather than the connections themselves, which will be covered by the boots.

13 While it may be desirable under production circumstances to use a simpler IR camera with fewer features, the camera should at least have the ability to account for the transmissivity of the window. Otherwise, the reported temperatures will be too low by a large margin (as seen in the Fluke TI10 images) and the differences between faulty connections and normal connections may not be large enough to generate an error condition.

14 Supplementary illumination will be needed to take visible images for context with the IR images. With no illumination at all, the interior of the cabinet is too dark for visible photography. The built in lamp with the camera sometimes allows adequate pictures but often creates a reflection on the window that obscures part of the image.

Best results appeared to be when an auxiliary light (flashlight) was shown in the window adjacent to the camera lens, or through another opening nearby. That opening could be a second IR window, if it was deemed necessary for avoiding line of sight obstructions. A lamp through a window at the top of the cabinet was inadequate to illuminate the target at the bottom of the cabinet and vice versa. Lighting built into the cabinet would solve the problem, but that would be a design issue for the manufacturer.

The practical tests mostly confirmed what was learned in laboratory testing. See Laboratory Test Report, October 23, 2015 for more information.

11 Summary of Field Test Results and Notes

During the individual tests, the following items were noted or determined:

1 Capturing all three phase connections in the same image is not possible with the existing setup. Field of view tests (Test A) showed that by pointing the camera at an angle, two phases of the connections could be captured in the same image, but not all three. To capture all three phase connections in the same image, the camera would need to be pulled back from the window a greater amount. However, the window would then not be large enough to see the entire scene given the natural field of view of the camera lens. This is not likely an issue as adjacent phases can be imaged together, but it is possible to equip these cameras with a wide angle lens, which may permit viewing of all three phases at once. The four inch round is the largest commercially available crystal window. Larger rectangular polymer windows are available, but they have the accompanying disadvantages of their reinforcement grids, and the larger windows may not be available in the clear polymer.

2 It was discovered in Test A that ergonomics may be a factor. The FLIR camera had the ability to angle the camera lens relative to the camera display. This was helpful when the windows were

down low or up high. However, it was still more comfortable for the operator to sit on a stool for the low window position and use a short step for the high window position. With a camera such as the Fluke where the display is in-line with the camera lens, this would be essential.

3 In Test B a fault condition was examined through the window. This test is for reference, as 4160V cabinets will not be built without dust boots over the connection points. Nevertheless, the hotter connection showed plainly, when imaging the connection lugs and also when viewing the cables below the lugs.

4 With the fault condition covered by the rubber boot in Test C, where the boot was not snug to the connection, it was not evident looking at the boot that there was a fault. This emphasizes that if a hot spot on the surface of the boot is to be the means for detecting faults, then the boot must fit very close to the connections, or be made of another material. An extenuating circumstance is that the boot being tested did not match the physical layout of the bus bar and cable, and thus there were gaps in the fit that allowed heat to escape, rather than build up under the boot.

5 Test D on taking visible images through windows reveled a secondary issue besides the reflection of the camera lamp noticed in the laboratory testing. By necessity, the visible camera lens is located some distance from the infrared camera lens. Where the thermal camera is held some distance from the target, this is typically not an issue. However, when the camera is held at close proximity to the IR window to get the best thermal image of the interior connections, this caused the visible camera to capture more of the window bezel and cabinet exterior than what was inside the cabinet. The result was to take a second image for the visible after repositioning the camera. This was a particular problem with the three inch window, but not as much of an issue with the four inch window.

6 In testing with the three inch window (Test E), it was certainly possible to obtain usable thermal images and also visible images. The field of view was large enough to image adjacent phase connections, provided there were no internal obstructions. The smaller window did create a number of issues that could be overcome by workarounds, but were certainly not convenient. Besides the above mentioned difficulty with simultaneous visible images, there were restrictions on the placement and angle of the camera at the window. With the FLIR camera, two measurement boxes were used to compare measurements between the suspected fault and another phase connection or another connection on the same phase. Because of the restricted camera placement, the location of the measurement boxes in the image had to be manually adjusted. This is a small thing and doesn't affect the ability to take useful images, but like the necessity to take a second visible image after repositioning, it adds time and effort to each examination being done. Over the course of a full inspection, this would represent a lack of efficiency.

Given the cost difference between the three inch and four inch windows is minimal compared to the cost of the cabinets (~$100 retail), it would be best to avoid these issues and use the four inch windows.

7 Test F was a repeat of the testing done in Test C, but with the boot reconfigured for a tighter fit and better position. Here the fault condition can plainly be seen, compared with that in Test C, again emphasizing the importance of tight fit of the boot. Also, this test explored the imaging of the cables as they exit the boot, with positive result.

8 Test G was also a reference against which the images through windows can be compared, since it is not permitted in many instances to use the thermal camera with an open cabinet. Measurements through the windows can be just as effective as those without windows, but the various restrictions mentioned above will drive a more careful set of procedures for imaging through windows, than would be needed if the cabinet was open.

9 The imaging with the alternate dust boot material (Test H) reinforced the conclusions from the tests with the red dust boot. Boot must be snug and the thermal imager will only be able to detect hot spots conducted through the boot material. More investigation will be needed to determine the reliability of thermal measurements taken on the outside of the boot, compared with temperature measurements taken of the cables exiting the boot. Both methods definitely reveal a fault condition using comparative measurements, but it was not possible to determine actual temperature measurements due to the jury rigged nature of the test setup with regard to attaching the boots.

10 Neither of the dust boot materials tested in Test F or Test H were transparent to infrared. It is beyond the scope of this project, but it would be worthwhile investigating whether an IR transparent material could be used to fabricate the dust boots. A crystal material such as was used in these windows is unlikely, but there may be an IR transparent polymer that might meet other requirements for the dust boots. Fabrication issues and cost would need to be considered.