

**Distributed Temperature Sensing for Inspection of Electrical Panels on Navy Ships**

**The National Shipbuilding Research Program**

**2017 Electrical Technologies Panel Project**

***FINAL REPORT***

May 2018

***Period of Performance: 16 January 2017 – 31 May 2018***

**Lead Investigator:**

**Penn State Electro-Optics Center (Penn State EOC)**

The Navy Manufacturing Technology (ManTech) Center of Excellence for Electro-Optics

222 Northpointe Blvd.

Freeport, PA 16229

**Jeffrey N. Callen – Technical Lead**

Research and Development Engineer

Electrical and Systems Engineering

724-295-7000, ext. 7141

[jcallen@eoc.psu.edu](mailto:jcallen@eoc.psu.edu)

**Sponsoring Shipyard:**

**Ingalls Shipbuilding (Pascagoula),**

**a Division of Huntington Ingalls Industries**

**Jason Farmer – Shipbuilder Technical Lead**

Project Lead / Electrical Engineer IV

228- 935-7573

[jason.farmer@hii-ingalls.com](mailto:jason.farmer@hii-ingalls.com)

**Project Technical Representative (PTR):**

**Richard Deleo**

**Newport News Shipbuilding**

(757) 688-9856

[r.deleo@hii-nns.com](mailto:r.deleo@hii-nns.com)

**DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.**

**Supervisor of Shipbuilding Gulf Coast,**

**SSGC C270**

**Clay Smith**

228-769-4721

[david.smith@supshipgc.navy.mil](mailto:david.smith@supshipgc.navy.mil)

Table of Contents

[Preface 2](#_Toc514245044)

[Executive Summary 3](#_Toc514245045)

[1.0 Background 4](#_Toc514245046)

[Integrated Project Team (IPT) 5](#_Toc514245047)

[2.0 Project Tasks 5](#_Toc514245048)

[2.1 Survey of DTS Technologies Available 5](#_Toc514245049)

[2.2 Bench Testing of Candidate Technologies 6](#_Toc514245050)

[2.3 Downselect to Final Candidates 9](#_Toc514245051)

[2.4 Field Testing/Final Demonstration 12](#_Toc514245052)

[3.0 Technology Transition 13](#_Toc514245053)

[3.1 Navy Supervisor of Shipbuilding Gulf Coast Perspectives [SSGC] 16](#_Toc514245054)

[3.2 Thermal Imaging Window Integration – Shipyard Impacts [Ingalls Shipbuilding] 18](#_Toc514245055)

[4.0 Conclusions 21](#_Toc514245056)

[5.0 Recommendations 22](#_Toc514245057)

[5.1 Potential Future Work 22](#_Toc514245058)

[6.0 References 24](#_Toc514245059)

[6.1 Other Advisors / Stakeholders 24](#_Toc514245060)

[6.2 Distributed Temperature Sensing System Requirements 24](#_Toc514245061)

[7.0 Appendix A Bench Demonstration Summary Report 27](#_Toc514245062)

[8.0 Appendix B Field Test Report 28](#_Toc514245063)

# Preface

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

# Executive Summary

Loose connections in electrical switchgear on Navy ships can lead to unsafe and costly electrical failures including arc faults. Current practices to detect these errors primarily involve infrared thermographic inspection of the connections looking for the hot spot that indicates a connection going bad. These inspections are done with open energized, equipment and the newer medium and high voltage electrical panels pose hazards to personnel, even with proper equipment and procedures. A previous NSRP project investigated using IR transparent windows to allow safer inspection of the higher voltage cabinets without removing the covers. That project also identified two issues with IR inspection through the windows: densely packed equipment in the cabinet can preclude line of sight to all points of interest and that all higher voltage connections are now covered with a silicone rubber dust boot. These boots permit hot spots to be seen through heat transfer, but an accurate temperature measurement is hard to make.

This current project investigated whether a fiber optic based Distributed Temperature Sensing (DTS) system could be used to make the required temperature measurements without the limitations of the line of sight and dust boot issues. In DTS, the sensors are either embedded in the optical fiber or the fiber is the sensor itself. This allows one optical fiber to be routed throughout the electrical cabinet, touching on each point of interest and lying beneath the dust boots. As the temperature is sensed directly, there is no line of sight to a sensor.

A set of requirements for the DTS system was drawn up and sent to vendors of four different DTS technologies. The technologies were Raman backscatter, Rayleigh backscatter, Brillouin backscatter and Fiber Bragg Gratings (FBGs). The first three take advantage of a natural phenomenon where a laser light is shown down the fiber and intrinsic non-uniformities within the optical fiber reflect the light back, where the electronics in a device known as an interrogator analyzes it. A disturbance at a location in the fiber, such as a temperature change, will move the reflected light in wavelength which the interrogator will interpret as a temperature measurement. The FBGs are different in that an interferometer is actually etched on the fiber which reflects light at a given wavelength. A temperature disturbance shifts that wavelength which is detected by the interrogator.

Based on responses to the requirements document and discussions with the vendors, the Brillouin system dropped out of the comparison as not being suitable for the application nor as economical as the others. The remaining systems were invited to the Penn State Electro-Optics Center to provide a benchtop demonstration. Two separate FBG vendors provided demonstrations.

The information collected and the results of the demonstrations were factored into a trade study. The Raman system and one of the FBG systems were selected as most promising and asked to participate in the final demonstration, which was in an actual Naval 4160 V panel. DRS Naval Power Systems in Milwaukee, WI, a member of the IPT, offered use of their prototype 4160V cabinet and test rig for the final testing. This test rig allows the actual 4160V cabinet to be tested with low voltage and high current. This simulates the heating of the connections and also allows for a fault to be safely simulated by loosening a connection. The Raman and FBG systems were both installed in the prototype cabinet and normal operation and simulated fault tests were run. Both systems were able to make the measurements and valuable information about the setup and use of the DTS systems was learned.

The primary overall conclusions of the project are:

* Either of the tested DTS systems is capable of making the required measurements for detecting loose connections in electrical switchgear cabinets.
* Neither of the systems has been used in this application before, so additional development work is required to produce a system ready for implementation on ship.
  + The Raman system must coil a certain length of fiber into a small area to provide the needed localized measurement point, and the prototype coils used in the experiment need to be developed into a repeatable and easy to make and install device.
  + The fiber between the Raman coils and between the FBG sensors will need to be ruggedized for installation on ship.
  + Neither system can process the temperature data on its own to make the required comparisons between the three phase connections. However, both systems can output temperature data in a form that can be processed by additional software to make the required determinations. This software will need to be developed.
* As this is a new technology, the design of the electrical cabinets and the design of the infrastructure on board the ship will need to be modified to accommodate it.
* The addition of continuously monitoring of temperature data allows loose connections to be detected before they become serious, thus reducing risk of a serious electrical issue such as an arc fault.
* The automatic data collection system opens up possibilities for health monitoring that is currently not possible, such as monitoring trends in current usage, monitoring temperature anywhere inside equipment and not just at the connections.

It is recommended that further development be explored to bring the capabilities of this technology to where it can be implemented in this application.

# Background

Shipboard electrical panels are inspected prior to delivery, during acceptance/sea trials, and at regular maintenance intervals to identify loose or incorrect connections that can potentially lead to dangerous and destructive arc faults and other failures. Currently, these inspections are primarily done by infrared (IR) thermography. A previous NSRP panel project investigated use of IR transparent windows for safer inspections so that the panel covers did not need to be opened. While this is a viable option, there are limitations to line of sight from windows due to obstructions within the panels and silicone rubber dust boots being installed over higher voltage connections. This project investigated the use of fiber optic Distributed Temperature Sensing (DTS) to measure the temperature of the electrical connections. With DTS, the optical fiber is the sensing element itself, and can be placed such that the line of sight issues with IR windows are eliminated. It also has the advantage that the sensing points are in series, along the same fiber, rather than in parallel, such as with thermocouples or other point measurement systems. Four distinct commercially available DTS technologies were examined and a trade study performed to compare each of them against the requirements for inspection on Navy ships. Bench top demonstrations were performed and the project culminated in a proof of concept demonstration in a relevant environment.

## Integrated Project Team (IPT)

Project execution was guided by the Integrated Project Team which consists of all funded participants including the lead investigator, sponsoring shipyard and government stakeholder, plus the project technical representative (listed on the title page of this document), as well as other advisors/stakeholders (see section 6.1 Other Advisors / Stakeholders). Other stakeholders that participated on our Integrated Project Team (IPT) include the NAVSEA Electrical Technical Warrant Holder office, LHA8 Electrical Subject Matter Expert (NSWCCD – SSES), and an industry representative; supplier for electrical distribution and power conversion components.

Stakeholder guidance and participation helped shape the requirements and conclusions of the trade study on the different DTS technologies so that the evaluation is relevant to the Navy shipboard environment.

# Project Tasks

The project started with a review of the issues with Infrared Thermography for inspection of electrical cabinets. From that review, a set of requirements was drawn up for a DTS system that would provide at least the same level of coverage and completeness as the currently used IR Thermography. This document included a section on General Requirements about form and function, Specific Requirements for the application of detecting loose connections and a set of Highly Desirable Features for the software appropriate to the application. Questions to the vendor about their systems followed. The LHA series of ship was used as a reference, due to use of 4160V cabinets and availability of data on it through HII Pascagoula, the sponsoring shipyard. The Requirements Document was vetted through this project’s IPT. This document is reproduced in section 6.2 at the end of this report.

## Survey of DTS Technologies Available

Four different DTS technologies were identified in this phase as possible candidates for the application. Potential vendors were also identified. The methods were:

* Raman backscatter. A natural phenomenon that occurs when the fiber is disturbed by a temperature increase. Uses normal fiber and the fiber itself is the sensor. Location is determined by the time the light takes to go down the fiber and return. Low spatial resolution, but long fiber lengths are permitted. The vendor is RSL Fiber Systems, LLC in East Hartford, CT.
* Rayleigh backscatter. Also a natural phenomenon. Uses normal fiber and the fiber itself is the sensor. Location is determined by the time the light takes to go down the fiber and return. High spatial resolution, but the fiber length is limited to about 50 m. The vendor is Luna Corp of Roanoke, VA.
* Fiber Bragg Gratings (FBGs) – each sensor is a miniature interferometer etched on the fiber itself. Therefore, the locations have to be planned before the fiber is installed in the cabinet. While COTS sensors are available, an array with a specific number of sensors for a particular electrical cabinet would be a custom product. Each sensor responds to a very narrow bandwidth. A temperature change shifts the bandwidth proportional to the amount of temperature difference. The interrogator notes which bandwidth shifted and knows the location of that grating. Very high spatial resolution. The number of sensors per channel of electronics is limited to the bandwidth available and the spacing of the wavelengths in the sensors. Two vendors were identified; Micron Optics of Atlanta, GA and Optromix of Cambridge, MA.
* Brillouin backscatter. This is also a natural phenomenon, but it is a very high frequency acoustic effect rather than photonic. In practice it is similar to the other backscatter techniques. A laser light is sent down the fiber and the electronics detect the backscatter effect from the point of temperature disturbance. Additional laser light is added from the other direction to provide an amplification effect. This requires two fibers per measurement channel. The vendor is OzOptics from Ottawa, ON Canada.

All of these systems are able to measure temperature through optical fiber, but none of them have been used in this particular application before.

The Requirements Document was sent to each of these vendors and the answers consolidated for the trade study for downselect. The document included a Request for Proposal to generate a rough idea of the equipment costs for a system the scale of an LHA ship. The Brillouin backscatter candidate dropped out at this point. The vendor indicated that it was much more suitable for long distance measurements and the vendor recommended using the Raman backscatter technique, which was less expensive. It was also not possible to arrange a demonstration of the Brillouin in the time available.

## Bench Testing of Candidate Technologies

Benchtop demonstrations were arranged with each of the remaining four vendors.

The Penn State Electro-Optics Center has a test setup where the connection between an external cable and the electrical bus bar can be simulated. Two such cable/bus bar connections are provided and each can be individually heated via resistance heating on the rear of the bus bar. This can simulate one good connection and one loose connection by setting the temperature differently on the two bus bars.

Vendors brought their equipment to Penn State and provided their own prepared demonstration if they had one. The equipment was then set up on the Penn State test rig to monitor two simulated electrical connections in a shipboard panel. A thermocouple was used to periodically spot check the accuracy of the temperature measurement reported by the vendor’s equipment. Further discussion was held on the practical aspects of installing the vendor’s equipment on a typical Navy ship. Notional sketches were provided to the vendor to indicate the possible distribution of measurement points within a typical cabinet and the distribution of cabinets throughout the ship. Vendors used this information to refine their proposals.

This is a summary of the results of each demonstration:

1. Micron Optics provided a demonstration of Fiber Bragg Gratings on August 25, 2017.
   1. Fairly small, low power interrogator. A sixteen channel interrogator is available.
   2. Sensors are typically sold as individual single measurement devices, but custom arrays with multiple sensors in series possible.
   3. Up to 79 sensors in series are available per interrogator channel.
   4. The total distance of a lead and sensing cable can be up to 5 km.
   5. Regular fiber lead cable can be used between interrogator and sensing cable.
   6. Sensor is in a metal case that can be screwed, welded, or epoxied to the surface. For the demo, the sensor was clamped. Design of the metal case decouples strain from the temperature measurement.
   7. Demonstration performed well on EOC test rig with sensor clamped. Readings close to thermocouple measurements.
   8. Provided an a la carte proposal with component costs. For the notional distribution of panels on a ship, the cost was $221,600 with 20% of that being electronics and the remainder in the sensors.
2. Luna provided a demonstration of Rayleigh backscatter on August 28, 2017
   1. Somewhat larger, but still low power interrogator. Each channel requires a small remote module at the far end of the lead cable to correct for local differences in ambient temperature and vibration.
   2. Sensor is a fiber optic cable. As sold off the shelf it is coated but not jacketed. It would need protection for installation in an industrial environment. A means of mounting would need to be devised into the protective covering. For the demo, the fiber was taped to the test rig. Strain would be decoupled by allowing the fiber to move in an outer sleeve. Measurements can be averaged along lengths of fiber for greater accuracy
   3. As the sensor itself is the fiber, the number of sensing points is determined by the spatial resolution, which is 5 mm, and the number of successive points being averaged. In practice, this can be over 1000.
   4. Sensor cable is limited to 50 meter length, but can make measurements as close as 5 mm apart.
   5. Lead cable is standard optical fiber. Presently 50 meters is longest demonstrated, but theoretically could be longer.
   6. As demonstrated, sensor was just fastened with tape. For practical implementation, would need to be encapsulated in some mechanical structure.
   7. Demonstration performed well on EOC test rig with sensor taped down. Some level of noise in the data attributable to jerry rigged installation, sensitivity to room conditions and no filtering applied. Readings close to thermocouple measurements.
   8. Proposed material cost of the system is $658,500 of which 98% is electronics. This is a consequence of the relatively short fiber and lead cable lengths, which drive the requirement for more electronics units than the other candidates to outfit a ship.
3. Optromix provided a demonstration of Fiber Bragg Gratings on September 7, 2017
   1. Rack mount, low power interrogator. An 8 channel interrogator is available
   2. Sensors are typically sold as individual single measurement devices, but custom arrays of multiple sensors are possible. Strain is decoupled from temperature via the sensor design. Also, depending on the range of measurement, the software can filter one or the other out of the measurement.
   3. Up to 20 sensors in series are available per interrogator channel
   4. The sensing cable can go out to hundreds of meters.
   5. Regular fiber lead cable can be used between interrogator and sensing cable.
   6. Sensor is in a metal case that can be welded or epoxied to measurement point. Vendor indicated willingness to create custom mount. For demo, sensor was clamped to test rig.
   7. Demonstration performed well on EOC test rig with sensor clamped. Readings close to thermocouple measurements
   8. Proposed material cost of system is $327,950 of which 38% is electronics, mostly because five 8 channel interrogators are needed to accommodate the required number of sensors, since the interrogators are limited to 20 sensors per channel. Multiplexers are available, but the tradeoffs still favor multiple interrogators. Vendor indicated that for production, much can be customized, including sensor mounting.
4. RSL provided a demonstration of Raman backscatter on September 8, 2017
   1. Rack mount ruggedized interrogator, power consumption unknown. A sixteen channel interrogator is available.
   2. Sensing uses regular jacketed multimode fiber that plugs directly into interrogator. As the fiber itself is the sensor, the number of sensing points will depend on the spatial resolution settings and the number of points averaged. In practice, it can be thousands. Spatial resolution for measurement along fiber can be 50 cm. Measurements require a 4x spatial resolution coil of fiber at each measurement point to get a good measurement. Measurements can be averaged along fiber.
   3. Maximum fiber length is up to 30 km depending on resolution settings, but at least 5 km, much more than needed for shipboard application.
   4. The lead cable is regular optical fiber, spliced to the sensing coils.
   5. This coil of fiber was placed on the test rig and secured by a wire tie. In practical application, the coil of fiber would need to be premade for easy and repeatable installation.
   6. Demonstration had difficulties with EOC test rig, with the system reported temperatures >10 °C below the thermocouple measurement. RSL began looking into the cause of this and methods for mitigation.
   7. Proposed material cost of the system is $78,740, of which 57% is electronics. This relatively lower cost is due to the long maximum fiber length allowing only one interrogator to be sufficient for one ship.

Details of all the benchtop demonstrations are included in the document, *Bench Demonstration Summary Report* (January 2018), which is reproduced at the end of this report as Appendix A.

## Downselect to Final Candidates

The trade study was completed once the bench demonstrations were finished and the revised proposals from vendors were received. The goal was to determine the best candidate to perform the final demonstration in the actual electrical cabinet and consequently would the most suited to the application.

During this period, a visit was made to Huntington Ingalls Shipbuilding in Pascagoula, MS to tour the LHA-7 ship (USS Tripoli) which was being outfitted at the shipyard. The types and distribution of 4160 VAC electrical panels was noted, so that a better idea was obtained as to what would be necessary to install a DTS system on such a ship. Issues regarding durability and possible installation difficulties were noted. This information was used to further evaluate the vendor proposals.

There were some factors that were common to all of the vendors. These were:

1. All interrogator electronic units are 3U 19” rack mount or smaller and use a 120 VAC 15 Amp circuit for power. No special cooling is required.
2. All can make multiple measurements per channel and have multiple channel interrogators available.
3. While some have more signal processing capability than others, none of the interrogators can make the desired measurements and comparisons with their internal software, however, all interrogators can offload data to a supervisory computer for analysis and alarms.
4. All interrogators use a laptop computer as a user interface for setup, programming and diagnostics. Once in operation the laptop is not required. If connected via network to another computer, presumably the UI software can run on the supervisory computer.
5. All can use standard optical fiber for connections between the interrogator and the sensing array, although some have length limitations.
6. All have various signal processing tools within their software to improve accuracy, such as selectable sample rates, temporal and spatial averaging, and more.
7. All have selectable measurement intervals, so data size versus sample interval tradeoffs can be managed. All are capable of running on their own, thus providing continuous measurement and ability to detect a developing issue before it becomes serious and to analyze the data for trends.

The results are summarized in Table 1.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Raman** | **Rayleigh** | **FBG (Micron Optics)** | **FBG (Optromix)** |
| Sensing | Anywhere along fiber | Anywhere along fiber | At embedded sensors1 | At embedded sensors1 |
| Points per channel | 1000 | >1000 | 79 | 20 |
| # channels/interrogator2 | 4 | 4 | 16 | 8 |
| Length limitation | 5 km | *50 m*3 | 5 km | 100’s of meters |
| Connection method | Splice | Splice or connector | Splice or connector | Splice or connector |
| Connection notes | Requires coil of fiber4 | Requires local module5 | *As is* | *As is* |
| Determine location6 | Calibrate or Measurement | Calibrate or Measurement | Construct per spec | Construct per spec |
| Bench test performance | *Read >10 °C low*7 | Within 2 °C of referenceT/C | Within 2 °C of referenceT/C | Within 2 °C of referenceT/C |
| Installation notes | Encapsulated coil8 | Ruggedize fiber9 | Screw, weld or epoxy | Epoxy or weld |
| Cost for LHA-710 | $78,740 | $658,500 | $221,600 | $327,950 |
| # of interrogators LHA-7 | 1 | *6* | 2 | 5 |
| % total cost electronics11 | 57 % | 98 % | 20 % | 38 % |

Table 1 DTS Method Comparison

Some notes from Table 1:

1. Fiber Bragg Gratings are etched at predetermined locations in the array.
2. Other numbers of channels are sometimes available, but these were recommended by the manufacturer.
3. Sensing cable is 50 meters maximum length, and lead cable is also 50 meters maximum
4. Raman requires minimum of 4 x the spatial resolution setting to be coiled around the measurement point.
5. Rayleigh requires an additional piece of equipment to offset local temperature and vibration effects.
6. Rayleigh and Raman both calculate position by length of time for signal to return. FBG are fixed by wavelength. Sensor with particular wavelength must be mapped to location.
7. Raman consistently reported lower than reference thermocouple. See below:
8. Raman fiber coil will need to be premade and encapsulated (potted) for ease of installation and to provide uniformity.
9. Rayleigh sensing fiber is coated, but not jacketed and would require ruggedization.
10. These are material costs only and do not include labor. These costs are for commercial grade systems and do not include non-recurring engineering costs to modify the systems for shipboard use. The type and distribution of electrical panels from LHA-7 was used as a comparison to develop these costs. A ship on the scale of the LHA-7 has roughly 30 electrical panels and over 800 separate measurement points on multiple decks across both sides and along the 900 foot length of the ship. Vendors were not shown this information, but their quotes were adapted and some assumptions were made. These assumptions were applied to all vendors. The results are not absolute costs, but are consistent between vendors for comparison purposes.
11. Percent costs of electronics is a measure of scalability. If an installation requires more sensors but not more interrogators, then a higher percentage electronics cost would be preferable.

Some key points in the comparison are shown in red in Table 1. The 50 meter length of the Rayleigh sensing cable and lead cable is a major limitation. In electrical cabinets with large numbers of connections, 50 meters of fiber may not cover all the required measurement points and another channel would be required. The limited lead cable means that an interrogator would need to be located close to the cabinets being monitored. As these cabinets are spread throughout the ship, additional (and expensive) interrogators are needed. While it is possible to reduce costs by using a single interrogator and plugging it into different sensing cables throughout the ship, this gives up the ability for continuous measurement and introduces reliability issues.

The Fiber Bragg Grating sensors can be used in their COTS form, provided it is acceptable to the cabinet manufacturer. They will need to be made into a custom array, however. Rayleigh requires an additional module at each sensing cable and the Raman fiber will need to be configured into coils to localize the measurement.

Raman has advantages in costs and length of fiber, but in the bench testing, suffered from inaccurate temperature measurements. The cause of this was not well understood at the time, since the Raman performed well in other applications. RSL continued to do independent research and consult with the equipment manufacturer to determine how this could be mitigated.

The bench testing results were presented to the project IPT and through discussion, it was determined that the Rayleigh system could be eliminated on cost grounds because of the fiber length limitations. At this point, RSL was making progress with the Raman accuracy issues, but it was still not sufficient and Raman was eliminated on performance grounds. Of the two FBG vendors, Micron Optics had the more applicable system, due to the larger bandwidth available per channel which allowed for more sensors per array and better economics. The IPT concluded that the Micron Optics FBG system should be invited to the final demonstration.

## Field Testing/Final Demonstration

DRS Naval Power Systems (now Leonardo DRS) in Milwaukee, WI provided a representative 4160V electrical cabinet for the final testing. This cabinet contains two three phase 4160V vacuum circuit breakers and the bus bars connecting them. DRS also supplied a test facility where the cabinet could be energized with low voltage and high current. This simulated the heating typically present in an energized electrical cabinet. This setup also allowed the loosening of connections to safely simulate a fault and the resultant high temperatures involved.

Due to difficulty in arranging schedules, the final testing was eventually arranged for April 24 and 25, 2018 in Milwaukee. In the intervening time, RSL had made sufficient progress in understanding the reason for the low temperature recordings. The main reason was that the system requires multiple (at least 8) spatial samples in order to produce an accurate reading. In the bench test, due to the amount of coil used and the firmware in the interrogator at the time, only 2 samples were being used. RSL obtained a firmware update and also developed a new method of making the coils, using increased number of turns of bend tolerant fiber. Tests at their facility showed good correlation with reference temperature readings. RSL was therefore invited to bring the Raman backscatter system to the demonstration in Milwaukee.

The DTS systems were set up with the sensing points where the external cable lugs were bolted to the bus bar connections at the rear of the circuit breakers. The Raman system recorded temperature at all three phases where the current came into the cabinet at the top and the Fiber Bragg Grating system recorded at all three phases where the current left the cabinet at the bottom. Note that while the connections at three phases were measured, the test set that generated the current was only one phase. Therefore the connections for the three phases were actually in parallel with each other, as split out from the test set terminals. Some differences in impedance meant the current was not exactly balanced between phases but this was evident in the temperature data that showed slightly different heating when the currents were different.

Five tests were run. A baseline test had all connections tightened properly and simulated normal operations. The second test loosened a connection at the top where the Raman system was monitoring, while the third test repeated this at the bottom for the FBG sensors. The fourth test loosened a connection on top and bottom at the same time but at a less severe failure simulation. The last test repeated this, but had the FBG sensors glued onto the bus bars with RTV rather than clamped as in the previous tests.

The significant factors learned in this testing were:

* Both the Raman backscatter system and the Fiber Bragg Grating (FBG) system were able to make consistent temperature measurements on the copper bus bars adjacent to the cable attachment points within the electrical cabinet.
* There were no fundamental technical issues that would preclude use of either of these systems for permanent measurement of temperatures at connection points within the electrical cabinets of Navy ships. All of the issues are concerned with a practical implementation within the manufacturing, installation and testing of the cabinets and in handling of the data to provide the required information.
* Both systems responded with reasonable data when presented with a simulated severe fault (rapid rise in temperature) and a simulated moderate fault (rise over time, but still faster than normal heating)
* Both systems provided accurate temperature measurements when compared with a thermocouple reference, particularly when the temperature change was not rapid. Both systems reported temperatures that matched the thermocouple within the accuracy of the thermocouple.
* The Raman system lagged the thermocouple readings during a simulated severe fault. This lay in the method of averaging selected within the system to process the raw data. This had been optimized for and worked well with slowly changing data. It was learned that these settings would need to be changed to accommodate rapidly changing temperatures if this is desired. There is a wide range of flexibility in these settings.
* The FBG system actually tracked ahead of the thermocouple during the rapid temperature rise. This was attributed to the thermal mass of the copper bus bar taking time to heat up where the referenced thermocouple was located. The FBG sensor was located right next to the cable lug where the simulated fault was created and responded more in real time. The sensing will be more accurate the closer it can be placed to the point of interest.
* Neither method as demonstrated is “production-ready”. The FBG system used off the shelf sensors that had no inherent method for attachment and the 1 mm fiber jacket between sensors would need to be ruggedized (with aramid fibers and a thicker jacket for instance) for installation in Navy ship cabinets.
* The Raman system required 4 meters of fiber to be coiled into a unit that could sense localized temperature. For this demonstration, these were hand wound and secured with aluminized tape. A plastic sleeve was placed over the fiber between coils to provide mechanical stability. For permanent installation, these coils would need to be premade with an attachment method built in and ruggedized fiber between them.

The full details of this testing are included in the document, *Field Test Report* (May 2018), which is reproduced at the end of this report as Appendix B.

# Technology Transition

None of the systems examined are ready for use in this application. Additional development will need to occur in several areas in order to transition the technology to a practical implementation:

* For the Raman system, the sensing coils will need to be developed into a form that is compact and easy to install into the electrical cabinet. This will likely be an encapsulated (potted) disc with some form of attachment feature built in. A repeatable method of fabrication is needed to ensure uniformity.
* Each Raman sensing fiber will need to be fabricated into a harness, unique to a particular electrical cabinet, with the sensing coils located at predetermined intervals and with ruggedized fiber between them.
* The FBG sensors will need to be fabricated with an attachment feature such as tabs for screwing or epoxy. Some COTS sensors have this feature, but the cabinet manufacturer will have input on whether they are appropriate.
* The FBG sensor arrays can be made with the sensors at specified intervals and ruggedized fiber between them. This is a custom order and these will need to be designed for each different electrical cabinet.
* The system interrogators will need to have their set up and data acquisition parameters optimized for this application. This is particularly true of the Raman system as there is wide flexibility as to how the system is set up.
* None of the systems can make the required comparisons of temperature automatically. To detect a loose connection, the temperatures for the three electrical phases must be compared to each other to find which one is hotter. As the temperature of all three varies with the electrical load, an absolute measurement or comparison is not appropriate. It is only the difference between the three that is significant. Therefore, the data must be exported from the interrogator to another computer for analysis. Both systems are capable of doing this, but the software to process the data will need to be written and tested.
* A computer will need to be designated to house this software and interface to the interrogator. For the Raman, the interrogator can output temperature data. For the FBG, only raw wavelength data is exported from the interrogator and additional software converts it to temperature. This software and the analysis software can reside on the same computer. This computer will also interface to the ship’s systems to register alarms and maintenance issues, if that is desired. It is possible that this computer might be the existing Machinery Control System (MCS) that already reads sensors and monitors multiple systems on the ship. Or it may need to be a separate computer entirely.
* Infrastructure to house the computer, interrogator and fiber runs to the electrical cabinets will need to be designed and fabricated.
* Neither of these systems has been tested to MIL standards, although MIL qualified optical fiber can be used as the lead fibers. Some form of qualification such as shock and vibration to Grade B MIL-STD-901D will be required, and other tests as determined by the Navy.
* Any new computer system will have to be reviewed against cyber security requirements and this may affect the options for running the required software and interfacing with ship systems.
* Some additional development will be necessary if it is decided that existing ships are to be retrofitted. It is imagined that the costs of retrofit will be considerably higher, as there is currently no provision for this equipment in the electrical cabinets or in the ship’s infrastructure.
* New procedures will need to be developed for installation into cabinets and onto the ship, test and operation, maintenance and troubleshooting, and repair.

Discussion with IPT members resulted in the following possible scenario for implementation once the development has been completed:

* The electrical panel manufacturer will design the fiber cable routing and attachments for each of the measurement points. A fabrication drawing and specification is sent to the fiber vendor. Each different panel will have a different part number for its fiber harness.
* The fiber vendor produces a fiber cable harness that meets this spec and delivers it to the panel manufacturer.
* The panel manufacturer installs the fiber harness as part of the assembly of the panel. It is possible that some preliminary testing can be done before the panel leaves the factory. It is still to be determined how to handle the measurement points where the shipyard connects cables to the panel. The harness may not be completely installed until then, or it may actually be a separate harness.
* The shipyard installs the panels on the ship. Each panel fiber harness either has connectors or a pigtail for a fusion splice where the fiber enters and leaves the panel.
* The shipyard installs the electronic interrogator(s) and runs the connecting fiber from there to each of the panels.
* At the panels, the shipyard connects or splices the connecting cable to the sensing cable in the panel. It is anticipated that each panel is chained to the next to the limits of the sensing technology, so that each channel of electronics has several panels in series.
* The shipyard connects the DTS electronics by network to a supervisory computer, such as the MCS that can examine the data and make the required comparison measurements.
* The shipyard performs the required setup or calibration as part of initial testing. For the FBG system, calibration data for the sensors in each array will be contained in a configuration file and downloaded into the processing software. For the Raman, the system does not know in advance the length of fiber between the interrogator and the sensing coils. The distance between coils inside the cabinet will be known from the manufacturing specification, but the amount of lead fiber between the interrogator and the first cabinet and between cabinets will likely vary somewhat at each installation. Either meticulous measurement will be needed, or some calibration procedure, where a heat source is applied to the fiber at the entrance to the cabinet and the interrogator can therefore register that point as the start of the sensing fiber.

## Navy Supervisor of Shipbuilding Gulf Coast Perspectives [SSGC]

### Business Case

The ability to prevent arc faults on Navy ships ensures mission readiness by keeping personnel safe and equipment operational. Faults typically occur as a result of loose or defective connections inside electrical enclosures. 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 infrared (IR) inspection on the enclosure.  This inspection typically requires the cover to be removed to allow the imaging device to see inside the enclosure. Generally, 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 as long as the inspector does not cross the plane of the equipment with the imaging device. At some installations, full arc fault PPE and exclusion zones are required, even for 450 V systems

Using thermal imaging devices to evaluate electrical equipment that is 450 volts or less continues to be beneficial in the prevention of faults and in the detection of faulty connections. This team has learned that the success of thermal imaging devices is solely dependent upon the ability to see the inspection points (i.e. connectors, bus joints, etc.). Because the enclosure cover is typically opened for 450V or less electrical equipment, thermal imaging devices work well.

With the Navy’s recent transition to medium voltage generation and distribution (4160V), an effective method of performing thermal imaging inspections on this equipment has been restricted due to OSHA & Navy prohibiting the removal of enclosure covers. A previous NSRP project consisting of the same team successfully integrated IR transparent windows to allow inspectors to use thermal imaging equipment to inspect 4160V enclosures without removing the covers. As a result of the project, medium voltage switchboard specifications now require IR windows.

The successful IR window NSRP project was not without limitations. Unlike the 450V or less IR survey where an inspector can remove the enclosure cover and move the IR camera to various angels to ensure all connection points are inspected, the IR windows do not provide a large enough portal to see every connection; in addition, the cable installation may block portions of the IR windows further limiting the view. Even with the limitations of the IR windows, the value IR windows provide in new 4160V enclosures far exceeds any costs associated with them.

The prevention of faults can be accomplished if one can detect a delta in the temperature between phases whether using IR camera, thermocouples, fiber optics temperature probes, or other temperature measuring device. In an attempt to remove the limitations discovered when using the IR window technology, the team wanted to evaluate the use of Fiber Optics Based Distributed Temperature Sensing (DTS) system to detect temperature deltas and determine the effectiveness of this technology.

From SUPSHIP Gulf Coast Code 270’s perspective, the use of fiber optics DTS to detect, alert, and potentially perform automatic operations is achievable.

Implementing Fiber Optic DTS will provide the following benefits to the US Navy:

**Eliminates the Current Infrared Inspection**

* The current process to perform an inspection requires using a thermal image device with special permission in accordance with the NSTM Ch 300. Equipment greater than 1000 volts 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 suits, 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 potentially prevent others on the ship from performing their missions.  Because this process is so disruptive, the test is usually scheduled really late in the day or at a time to minimize disruption.

**Provides Continuous Monitoring**

* Because the Fiber Optic DTS system is permanently installed the likelihood of detecting a loose connection or a condition which will lead to a fault is greatly improved.   Due to the aforementioned factors, there is a chance some issues may not be able to be detected using the Thermal Imaging device.

**Reduces Manpower**

* The crew or special team will no longer be required to come onboard a ship to perform the manpower extensive inspections. The continuous monitoring eliminates the need to perform dedicated inspections.

**Ensures Adequate Inspection**

* Especially with 4160V enclosures, many of the connections and bus joints are difficult to see or inspect. Some connections have creepage boots or sleeves over the connections making it difficult to inspect using a thermal imaging device. Using a permanently installed system such as the Fiber Optic DTS ensures all critical areas are properly monitored. From the beginning of the enclosure design, a systematic approach can be used to ensure the system is monitoring the desired areas.

While the benefits of a permanently installed temperature monitoring system outweigh the concerns, below are some areas which need to be considered before implementation:

**Potential Cost**

* The system material cost of the Fiber Optic DTS system is not too concerning, but the cost associated with the implementation, installation, and testing for the enclosure manufacture along with the cost associated with the shipbuilders need to be evaluated to ensure feasibility.

**Installation and Maintenance**

* The delicacy of fiber optics, especially inside an enclosure containing very large copper cable may cause some challenges during initial installation and maintenance (such as annual cleaning).

This technology is phenomenal and will no doubt be implemented somewhere on a US Navy ship in the future. Using it as a temperature monitoring system inside electrical enclosures is likely, and this project proved the technology will work for this application. Once the industry team can determine a means to make it robust and easy for the shipbuilder and enclosure manufacture to implement we will likely see this technology inside our medium voltage enclosures.

## Thermal Imaging Window Integration – Shipyard Impacts [J.P. Farmer, Ingalls Shipbuilding]

## Discussion

## Technology Need & Design Impact

A safe and reliable method of inspecting and monitoring electrical connections is needed as the U.S. Navy is transitioning to increased use of medium voltage systems. As determined in the previous NSRP Panel Project, “Safer Thermographic Inspection of Medium Voltage Electrical Panels on Navy Ships”, the use of IR windows provides for inspection of some connections; however line-of-sight issues preclude this from being an ideal solution in all cases. Implementation of a DTS system would enable all applicable connections to be thermally monitored. This additional capability would allow a loose connection to be identified prior to an arc flash incident – eliminating costly equipment damage and potential for injury to personnel.

## Current Shipyard Inspection Processes

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. These thermal inspections are currently conducted on 450V boards only due to safety concerns.

Inspections are done on low voltage (450V) equipment as standard practice. This process includes removal of the panel cover and 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.

## Impact to Current Shipyard Processes:

Potential impacts at the shipyard level will include changes to engineering documents, installation processes, test procedures, test equipment and trades involved in installation and testing processes. The extent of these impacts will be dependent on the DTS system design and installation approach selected. As noted herein, multiple DTS systems were investigated and have the potential to capture the necessary thermal measurements. Whether a Fiber Bragg Grating (FBG) or Raman backscatter system is selected, either system would require additional development, including system design, software interface, and installation methods for the intended shipboard application.

Potential installation options range from the DTS system being fully integrated into the electrical switchgear by the manufacturer to installation of sensors and interrogator at the shipyard. If the system were fully integrated at the manufacturer, the DTS system would be part of the cabinet. In this scenario, impacts could be as small as an additional communication link to the cabinet. Likewise, if the DTS unit were to require installation of the sensors and interrogator units by the shipyard, a significant change to existing processes would be required. In this scenario, an additional trade would be involved in the switchgear installation to handle the fiber optic component installation and testing.

In either scenario, testing processes would be impacted. Testing to verify connection integrity could be conducted using the DTS system. This would eliminate the need for the Electric Plant Infrared Survey testing in 450VAC systems and would provide a safe method for inspecting medium voltage (4160VAC) systems.

## Cost Savings Opportunities & Business Case

The implementation of a system with the capability to monitor electrical connections as demonstrated by fiber optic DTS systems would give personnel sufficient advance warning to eliminate arc flash incidents associated with loose connections. This increased capability would provide benefits including avoidance of cost associated with equipment damage, equipment removal, and personnel injury. An arc flash incident can cause catastrophic damage to equipment. The removal of damaged equipment may require access cuts be made in the ship’s structure. This process is very costly and impacts construction schedule. These costs are in addition to the cost to replace the damaged equipment.

Benefits could be observed from new construction through the ship’s service life. The system would provide the ability to monitor connections from initial operation of the electrical equipment. This could eliminate the need for the Electric Plant Infrared Survey conducted during ship construction activities. After ship delivery, the system would provide continuous monitoring capability that could eliminate the need to conduct routine thermal surveys of equipment connections.

## Conclusion & Recommendations

New methods of inspecting medium voltage switchgear are needed to reduce risk of equipment damage and to ensure personnel safety during the inspection process. This project evaluated fiber optic distributed temperature sensing options as a method of monitoring electrical connections. Benchtop demonstrations, laboratory testing, and a formal trade study were conducted. Two systems were selected for testing in a relative environment. Data collected determined that both systems are capable of making the necessary measurements with satisfactory accuracy; however additional development is needed to field a system for specific shipboard applications.

Shipyard impacts will be dependent on the final system design and installation methods. Implementation of a DTS system could eliminate the need for Electric Plant Infrared Survey conducted during the ship construction process. Additionally, arc flash incidents associated with loose electrical connections could be prevented resulting in avoidance of costly repairs, schedule delays, and personnel injury.

Further development of this technology is recommended. The monitoring capabilities of a DTS system as demonstrated in this project would provide benefits to the Navy and shipbuilding industry.

# Conclusions

The goal of the project was to determine whether a fiber optic based Distributed Temperature Sensing system could make the required temperature measurements to find loose connections in electrical switchgear. The purpose is to overcome the difficulties of restricted line of sight and dust boot covers that hamper IR thermography inspection through IR windows.

The project examined four distinct technologies for DTS and concluded that two of them (Raman backscatter and Fiber Bragg Gratings) are applicable in technical performance and economics. No fundamental issues were identified that would preclude such a system being used to detect loose connections. However, neither system has been used in this application before, so further development is necessary to create a practical system that could be implemented on ship.

This development is primarily in two areas, the sensing itself and the processing of the data.

* For the Fiber Bragg Gratings (FBGs), COTS sensors exist that are close to what is needed, but a custom array of them for implementation throughout multiple sensing locations on the ship will need to be designed and fabricated. For the Raman system, the fiber itself is the sensor, so in order to make measurements at a local point such as an electrical connection, the fiber must be coiled. The prototype measurement coils that showed proof of concept will need to be matured to reproducible, easily made and easily installed units. For both types, the fiber between and leading to the sensors will have to be ruggedized for shipboard installation.
* To detect a loose connection, the temperatures from all three electrical phases of a circuit are compared to see if one is hotter than the other two. Neither of the systems can make this comparison internally. Each can export the temperature data to another piece of software. This software will have to be developed, but it has the straightforward tasks of segregating measurements from the same circuit and comparing values between them.
* There will be additional development effort to build a system like this into the electrical cabinets and also to provide the infrastructure for it in the ship design.

The benefits of a system like this include:

* The present IR thermography method is a spot check that is done at intervals of weeks or months and problems can develop between inspections. The DTS is a continuously monitored system that can automatically detect connections coming loose before they develop into serious problems.
* This project used the 4160V cabinets in a ship of the LHA series as a reference for implementation needs, but these systems are scalable to higher voltages and larger or smaller ships.
* Once an automatic monitoring system has been put in place, it opens up possibilities for system health beyond just looking for loose connections. Temperature on other things can be tracked, such as rotating parts. Trends can be tracked so that a system health within the electrical load can be inferred. For example, an increase over time of all three phases of current supplying a large motor may indicate a failing bearing in the motor. In the case of the Raman system, the fiber itself is the sensor, so data can be extracted from the lead cable between the DTS electronics and the electrical cabinet. This can be used to determine the heat in adjacent electrical cables in the same cable tray or even as fire detection wherever the fire runs.
* During the field testing, at times there was evidently some electro-magnetic interference with the thermocouple readings being used as a reference. The cause was not determined, but it illustrated that the fiber optics are unaffected by EMI in the electrically noisy environment of high voltage electrical switchgear.

The proof of concept has been demonstrated that these DTS systems are technically feasible to make the required measurements and overcome the limitations of the IR thermography. The potential benefits of having such a system suggest that the additional development required should be pursued to make them into a system that can be implemented in a production setting.

# Recommendations

The overall recommendation is to further develop DTS into a practical system that can be implemented on Navy ships by addressing the ruggedization of the sensing cable design and developing the software to process the data for this application.

The effort will require close coordination between DTS and fiber manufacturers, the electrical equipment manufacturers, the shipyards and the Navy so that all aspects of implementation, training and usage are addressed.

## Potential Future Work

This project has seen the potential benefits of automatic temperature measurement to detect loose electrical connections. The next steps in developing the technology toward the practical application will include:

1. The Navy and industry should together develop detailed specifications as to what the target production system will look like and specify requirements for performance, environment capability and future expansion, all of which will have an impact on system cost.
2. Additional testing of each system in a controlled environment against a trusted reference should be done to characterize the performance under all conditions expected to be encountered. This will allow things like the coil construction and software settings for the Raman system and the attachment method for the FBG system to be refined and optimized for this application.
3. A practical design for sensor harnesses will need to be developed. For the Raman system, this involves making the coils into an easily produced and easily implemented sensor and ruggedizing the fiber between them. For the FBG it will involve selecting a sensor with a workable attachment mechanism and ruggedizing the fiber between them.
4. Develop the software to process the raw temperature data and extract the desired information. This involves exporting the data from the system interrogators, grouping the measurements so that the three phases from the same circuit can be compared, and developing code that creates alarms when the required conditions have been met.
5. Some deeper economic analysis should be performed for the cabinet manufacturer’s costs to implement, the shipyard costs to install and long term maintenance costs. This project only examined tradeoffs within the context of a ship the size of the LHA series. The analysis should be expanded to other class ships to see where the trade space lies.
6. Additional capabilities for these systems should be explored. Once an automatic temperature measurement system is already installed, then the software and settings to perform other monitoring besides loose connections and to monitor trends and analyze historical data can be developed.

# References

## Other Advisors / Stakeholders

**Dave Mako**

**Naval Surface Warfare Center, Carderock-Ship Systems Engr Station, NSWCCD-SSES C937**

215-901-5926 (office – Philadelphia)

[Charles.mako@navy.mil](mailto:Charles.mako@navy.mil)

**Gary Weiss**  
**DRS Power & Control Technologies, Inc**

Business Development Manager for Power Distribution and Power Conversion  
4265 North 30th Street - Milwaukee, WI  53216  
(414) 875-4816 (Office)

[garypweiss@drs.com](mailto:garypweiss@drs.com)

**Christopher Nemarich**

Naval Sea Systems Command, NAVSEA 05Z32 Electrical Distribution Systems (Office of TWH)

(202) 781-0413 (office)

[christopher.nemarich@navy.mil](mailto:christopher.nemarich@navy.mil)

## Distributed Temperature Sensing System Requirements

The following document was supplied to DTS vendors to evaluate their product against the requirements for this application.

Distributed Temperature Sensing System Requirements 6/16/17

1. General Requirements
   1. System is targeted for 4160 VAC Three Phase electrical switchgear placed in multiple locations within a Navy ship
   2. System must sense temperature at multiple points.
   3. System must be able to uniquely identify the point at which each temperature measurement is being taken.
   4. System must not interfere with normal operation of electrical switchgear.
   5. System readings must not be affected by normal operation of electrical switchgear.
   6. System must be able to display readings at specific points on demand
   7. System must be able to cycle through all measurements within 30 minutes.
   8. System sensing elements must be able to be installed or designed into switchgear without extensive design modifications that would alter the size or functionality of the switchgear cabinet.
2. Application specific Requirements
   1. System must read temperature with ≤ 1 °C resolution.
   2. System must read temperature with +/- 2.5 °C accuracy. (IR Thermography chart requires notation to be made at ≥ 5 °C difference between phases.)
   3. System electronics must operate within 25°C to 65°C temperature range (or be modified to meet that requirement)
   4. System sensing elements must operate within 25°C to 95°C temperature range (or be modified or substituted with to meet that requirement).
   5. System electronics must meet shock and vibration requirements of Grade B MIL-STD-901D (or be able to be modified to meet such standards)
   6. System sensing elements must meet shock and vibration requirements of Grade B MIL-STD-901D (or be able to be modified to meet such standards)
   7. System will allow for one sensing element (fiber) to run into one cabinet, out of that cabinet and into another, and so on for multiple times. Connectors and/or splices may be needed to facilitate this feature.
   8. An individual cabinet may contain between 20 and 75 points of interest where temperature is to be measured. Measurement points can be physically as close as 6 inches to each other or as far apart as 24 inches.
   9. The system should be able to measure temperature at up to 800 individual locations. A combination of multiple sensing elements and multiple electronics units may be required to accomplish this.
3. Highly desirable features
   1. System is programmable to compare measurements against each other and display the results, specifically, compare temperatures of three electrical phase connections in the same circuit. In general, three measurement points (which may or may not be adjacent along the length of the fiber) are grouped together. The system will be able to display temperatures for each member of this group compared to the other two. There will be many sets of these groupings.
   2. System has the ability to set alarms based on comparative measurements, for example, if one phase connection in a circuit is more than 5 °C warmer than the other two comparative phases in the same group. It should compare and alarm if any of the three measurements exceeds the other two measurements within the group.
   3. System has the ability to store data and/or offload data to an electronic storage device, including alarms.
   4. System has the ability to make measurements, evaluate alarm conditions and store data on a programmable schedule, up to days or weeks between measurements.
   5. System has the ability to display or alarm on trends in the data, specifically programmed. For example, temperature data for one phase versus the other phases tracked over days or weeks.
   6. Optional: Alarms can be tied into hardware outputs that can drive external actions such as indicator lights, etc.

Questions for Vendors

1. Can the system meet the attached requirements, including the highly desirable features?
2. How many measurements can be made on a single fiber?
3. How many channels can the system accommodate?
4. What is the temperature resolution?
5. What is the temperature accuracy?
6. What is the spatial resolution?
7. What is the longest distance for a single fiber sensor?
8. Are there any installation considerations, such as how fibers need to be attached to the measurement point (laid adjacent, screws or clips, adhesives, etc.), whether there is a minimum length of fiber required to touch the measurement point to assure adequate signal to noise, etc.?
9. Is the system sensitive to other disturbances besides temperature differences? If so, how are they distinguished from each other or how is the influence of the other mitigated so as to get the desired measurement?
10. Does a temperature disturbance in one location on the fiber affect the measurements of locations in the same fiber beyond that location? In other words, can the system register two or more temperature events on the same fiber with the same accuracy and resolution?
11. Does the system need calibration after installation? If so what is involved?
12. Does the system need periodic calibrations after being in service? If so, how often and what is involved?
13. Are any of your systems qualified for military use?
14. Can the electronics (interrogator) be separated from the fibers on a regular basis? That is, if desired, can a single electronics unit be carried to one location, hooked up to the installed fibers and measurements taken and recorded, then disconnected and taken to a different location and the measurements repeated there? This trades off continuous monitoring with a permanent installation using multiple electronic units for the cost savings of using a single electronic unit to make periodic measurements at different locations.
15. As an example, assume there are switchgear cabinets on 5 separate locations with unknown spacing which could be several hundred feet apart.  Each cabinet will have 40 to 75 measurement points within it, or about 150 measurement locations at each location.  How would you configure a system to measure all of these points?
16. What would be the rough cost of this system? Assume that costs to get your system military qualified (if it is not) are not included at this time.

# Appendix A Bench Demonstration Summary Report

Double click on first page below to open and print PDF.



# Appendix B Field Test Report

Double click on first page below to open and print PDF.

