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Guide for the Application of Distributed Fiber Optic Temperature Sensing to Underground Power Cables

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PRODUCT DESCRIPTION

Background

Temperature measurements using junctions of two dissimilar metals – a thermocouple – have been around since the 1800s. The thermocouple was relatively simple to configure, rugged, and reliable, and has been applied for many years to all sorts of process controls, as well as used for temperature monitoring on underground cable systems since the 1950s. Thermocouples would be fitted to locations that were anticipated to be hot spots. Unfortunately, this often meant the large sections of the cable system would not be monitored.

In the 1920s, physicists studied the scattering of light (photons) and the characteristics of the scattered light as related to the medium in through which it was passing. It was discovered that a backscattering effect, called the Raman Effect, was affected by the temperature of the material causing the backscatter. In the 1980Sthe principles of the Raman Effect were combined with fiber optic equipment used in the telecommunication industry to permit measuring temperatures along a fiber. This technology was used in manufacturing and petroleum industries and eventually with power cables. The advantage for the cable industry was that nearly a continuous measurement of a buried cable system could be done.

EPRI began applying distributed fiber optic temperature sensing (DFOTS) beginning in the mid-1990s to member utilities looking to optimize, and potentially increase, the ratings on existing underground cables, or to provide as-built verification of the design ratings on new cable circuits. In these early days, there was only one supplier of equipment and the equipment was fairly expensive. At that time EPRI purchased a unit for testing at cable-using utilities.

Though many more commercial installations have taken place, and there are now more than one vendor, many utilities still face uncertainties and challenges to the successful application of DFOTS technology to cable systems. In response to this challenge, EPRI developed this application guide to help utilities in assessing the selection and application of DFOTS technology.

Objective

The goal of this guide is to take away some of the uncertainty of using DFOTS with underground power cables by describing how the equipment works, and the current state-of-the-art of fiber-based temperature measurements, discussing the benefits of different types of installations of DFOTS equipment, highlighting some of the challenges to using the technology, and a means to interpret the results. Ultimately, the goal here is to educate and guide utilities in the evaluation and application of the technology.

Approach

The approach to developing this guide was to contact DFOTS equipment suppliers and get a general understanding of the state-of-the-science. This information was combined with EPRI's background information on DFOTS systems from the various EPRI projects that have utilized DFOTS methods as a basis for case studies. A general implementation strategy is provided so that engineers at utilities can make more informed decisions about applying DFOTS technologies.

Keywords
Ampacity
DFOTS
Distributed temperature sensing (DTS)
Extruded cables
Monitoring
Temperature measurement
Underground power
Underground transmission
Uprating

ABSTRACT

This report summarizes distributed fiber optic-based temperature measurement technologies and how this type of technology can be applied to underground power cables through case studies, implementation strategies, and technical details of applying these systems.

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1
INTRODUCTION AND BACKGROUND

1.0 Introduction

Temperature monitoring of underground cable systems, like most electric power equipment, is important to evaluate the operating conditions of the system. Underground power cable ratings are limited by maximum allowable temperature to avoid irreversible damage or accelerated aging of the cable system; usually the constraint is the insulation material temperature immediately adjacent to the conductor.

Rating methods such as Neher/McGrath or IEC60287 are used to relate cable circuit loading and the resulting heat losses to the operating temperature. Software tools such as EPRI's Underground Transmission Workstation and Dynamic Thermal Circuit Rating can be used to perform these evaluations, respectively, for design or off-line calculations and in real-time.

During cable system design, conservative assumptions are often made so that the cable circuit(s) can carry the required load without exceeding the rated temperature, and the cable system is operated with the intent that the applied load will not cause excessive temperatures. However, there are practical limitations to adequately evaluating the conservative assumptions. For example, soil thermal resistivity is usually only measured every couple thousand feet along the cable trench. The ambient soil temperature can also vary as a function of surface type as well as proximity to other heat sources. Seasonal variations in ambient temperature and external heat sources mean that these characteristics are not static. Burial depth and other installation characteristics also typically vary along the length of a cable circuit. These many factors mean there is uncertainty, even with careful consideration, of the various parameters. A means to get better information about the operating temperatures of the underground cable system along the entire route is invaluable to optimizing the rating, to maximize power transfer, and avoid damaging the installed cable system.

The Institute of Electrical and Electronics Engineers (IEEE) has produced a guide on temperature monitoring of cable systems (see references) that provides a comprehensive discussion of various temperature monitoring techniques.

1.1 Temperature Measurement Background

1.1.1 Thermocouples

Temperature monitoring has traditionally been done using thermocouples. A thermocouple measures temperature by monitoring the current that is generated by two dissimilar metals that are in contact; the magnitude of the current generated is related to the temperature where the two metals are in contact. The contact point is called a junction. A meter or data logger is used to read the thermocouple by forming a similar junction internal to the device which completes the circuit through which the current is measured to determine the temperature. Meters provide for

instantaneous measurements or short-term monitoring while data loggers can record temperatures every 15 minutes or so for several months. Thermocouples may also be tied into remote terminal units (RTUs) for continuous monitoring by utility SCADA systems.

Several types of thermocouples are available that utilize junctions of two different metals. Type-T thermocouples are most commonly applied to cable systems because their operating range (-200°C to 350°C) is most closely the range relevant to operating temperatures of cable systems. A Type-T thermocouple uses a junction formed between copper and constantan wire.

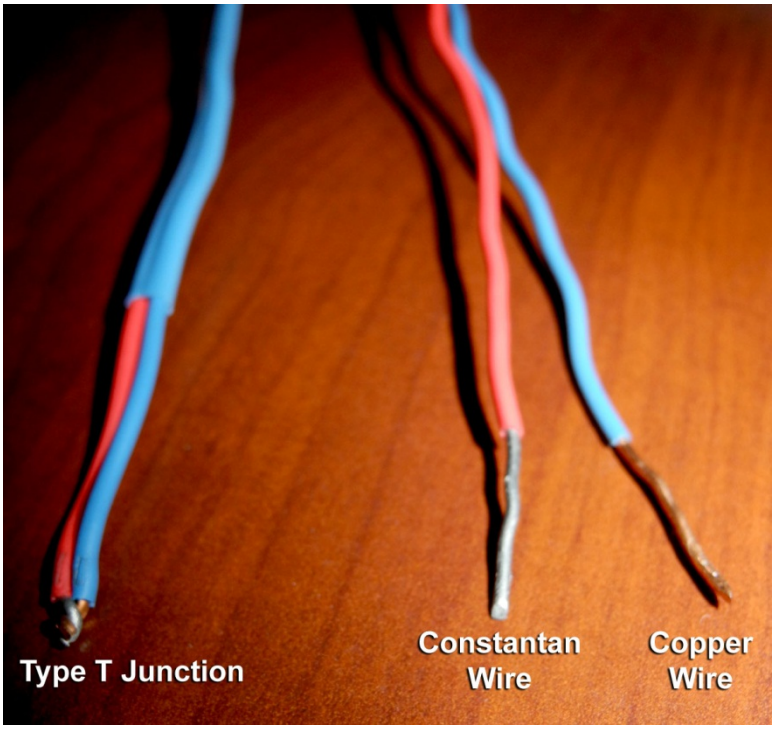


Figure 1-1
Thermocouple junction formed of constantan and copper wires

Thermistors are an alternative type of point sensor based on solid state technology and where very high accuracy is important. Thermistors are generally less durable than thermocouples and are infrequently used for field monitoring.

Thermocouples can be used for measuring ambient earth temperature at one or more locations. A range of burial depths can be monitored, creating a thermocouple tree. Thermocouples may also monitor cables including the:

- Outside of a cable pipe
- Outside of a cable jacket
- The annular air space between the cable jacket and a conduit
- The outside of the conduit
- An external heat source
- Another point in the cable system

The thermocouple is a simple means of measuring or monitoring temperature as they are relatively inexpensive and reliable. However, there are some inherit disadvantages:

- Thermocouples are constructed from metal conductors that can be affected by induced currents and/or voltages, especially when the lead lengths are long (more than 50 feet or so).
- Thermocouple lead lengths are constrained to a few hundred feet (extension grade wire could permit measurements to no more than 1000 ft typically).
- Each thermocouple junction measures temperature at only one location. Practically, it is not possible to monitor temperature for more than a few tens of locations at best.

Since cable ratings are a "weak link" analysis whereby the worst combination of installation conditions, ambient temperature, external heat sources, etc. (i.e., the weakest link in the chain) the limitations of thermocouples constrain their effectiveness at monitoring temperatures on cable systems. Cable installation and environmental conditions can change significantly over relatively short distances and multiple times over the length of a several mile underground cable circuit. The localized nature of thermocouple-type measurements and the potential for electrical interference can sometimes limit the effectiveness for monitoring cables directly although thermocouples still are useful for spot measurements, ambient temperature measurements localized to substations or other convenient access points and as a means to calibrate DTS/DFOTS systems.

1.2 Fiber-Based Temperature Monitoring (Point Sensors)

Initially fiber optic wire was merely the transport medium for the light to pass down to an ampoule filled with a phosphorescent material that would change the incident light's wavelength with temperature.

Many of the types of sensor modes – encoder, reflection/transmission, gratings etc. – all work off of similar principles in that the fiber makes a contact or the light coming out of the fiber impinges onto a substrate, mirror, or Fabry-Perot etalon (simple Fabry-Perot interferometer placed at the end of a fiber where there are at least two reflecting parallel surfaces). The spacing of the two reflecting surfaces provides for the interference of the incident and reflected light back at the source. The main difference between an etalon and interferometer is that the etalon has a fixed spacing between the plates for a specific measurement only (wavelength and resulting pattern). A standard interferometer can be adjusted providing a variety of interference patterns for many wavelength separations.

EPRI had funded such research in the early 1970's with the application of transformer temperature measurements. While a good idea, this technology still required the technician to use the proper spectrometer to measure the wavelength of the reflecting light and interpret the measured temperatures. Some companies started then to develop an all-in-one approach making it easier to perform measurements. Luxtron was one of the first to develop commercially viable systems.

While these types of systems avoided issues with induced voltages and currents and potentially allowed the fiber to pass through mediums that might not have been suitable for metal sensor leads (i.e., in areas of high voltage or high electric field), the application of fiber-optic based point sensors was similar to that of thermocouples. Fiber optic-based point sensors were not used extensively with cables.

1.3 Fiber-Based Temperature Monitoring (Distributed)

Installation conditions for cable circuit(s) in a trench can vary over a few feet longitudinally along the trench, casing, or underwater route. Therefore, cable temperatures should ideally be monitored every few feet to detect these variations that will result in similar variations in operating temperature. Factors that influence these variations include:

- Burial depth
- Cable separation among phases and circuits
- Separation between the cables and adjacent utilities
- Heat sources (other cables, steam or water lines, etc.) that may be crossing or running in parallel with the cables
- Variations in soil thermal resistivity
- Variations in ambient temperature either due to depth, surface conditions, or solar radiation

A distributed temperature measurement system that can detect these variations along the cable route is a valuable resource to verify the current-carrying capacity of the cable system and monitor the system to avoid exceeding accepted operating temperatures. A fiber installed in parallel to the cables can monitor the temperature of the cable every few feet along the length of the circuit.

Distributed fiber-optic temperature measurements depend on the scattering of light (photons) pulses when they encounter crystals within the glass fibers. A physicist discovered one particularly type of scattering that occurs, and the “Raman” effect was named after him. This type of technology has been used for spectroscopy of materials in various states.

For distributed fiber optic temperature sensing, an incident photo beam from a laser diode is injected into the optical fiber (use of the laser is associated with “stimulated” Raman amplification or scattering) which results in various types of reflections, called “scatter”. Essentially, the material through which the light at a particular wavelength[1] passes either gains or loses energy from interactions with the surroundings; the resulting scattered light has either lower (Stokes) or greater (anti-Stokes) energy. The Stokes scatter is temperature dependent while the anti-Stokes scatter is not. The scatter is measured by specialized electronics (described below).

While some signal loss may occur as the fiber length increases, the ratio of the Stokes to anti-Stokes can be evaluated to determine the temperature in the fiber.

[1] The wavelength of light is determined by the type of laser used.

1.3.1 Definitions Relating to Distributed Temperature Sensing

There are some definitions that may be helpful in understanding parts of this application guide. These definitions are in the context of the subject matter of this guide and may not be relevant for other applications or industries.

- OTDR is an abbreviation for optical time domain reflectometry (or reflectometer).
- OFDR is an abbreviation for optical frequency domain reflectometry (or reflectometer).
- Spatial resolution is the distance between adjacent temperature measurement points along a fiber. In general, it is appropriate to consider that a measurement is obtained by averaging the characteristics over +/- half the spatial resolution.
- Temperature resolution is the minimum difference that the fiber optic sensor can resolve in making temperature measurements.
- Temperature accuracy is the ability to correctly monitor the temperature; calibration of the equipment relative to known values may be used to optimize accuracy.

1.3.2 Types of Distributed Temperature Monitoring Systems

Two types of DTS equipment exist.

The first type is based on an optical time domain reflectometer (OTDR) that is commonly used in the communication industry to measure optical signal loss in a fiber. The traditional purpose of this type of testing was to evaluate overall signal loss, including through fiber splices, along the length of a fiber. The strength of the signal for traditional OTDR to measure fiber loss characteristics is significantly greater than the Raman scatter that is used to measure temperature. OTDR-based temperature measurement equipment is the most common. The typical length of fiber testing may be up to 18-20km with a spatial resolution of 0.5-1.0m.

An alternative method based on “frequency domain” methodology uses Fourier Transform analysis to evaluate a measured backscatter signal for the entire fiber optic being tested. Since the Raman backscatter signals that are of interest occur over relatively narrow wavelength bands, the Fourier Transform filters out the signals of interest for evaluation. The main benefits to this approach is that fibers that are longer (perhaps up to 25km) in length may be tested and with finer spatial resolution (0.1-0.25m); measurement times may be faster than time domain-based measurements. However, the signal processing is more difficult.

There are other types of distributed temperature sensing such Bragg fiber gratings or Brillouin light scattering. However, Bragg gratings are used for focused temperature measurements over short distances. Brillouin backscatter can be used for purposes such as monitoring strain or temperature, but no commercially available systems were identified for application to power cables.

1.3.3 Basic Configuration of DTS Equipment

Most DTS equipment consists of a laser that sends a series of pulses into an optical fiber. Each pulse passes through a coil of fiber within the DTS equipment that is also connected to a thermistor or thermocouple. The DTS equipment uses this known reference coil temperature to perform a level of self-calibration. Connectors on the ends of the sensor fibers are attached to

ports on the back of the DTS fiber; these “unknown” fibers also receive the laser pulses. The DTS equipment sends a series of laser pulses into the reference coil and connected fibers to stimulate Raman backscatter that is then measured by a receiver within the DTS equipment.

By successively sending laser pulses into the fiber(s) and waiting varying amounts of time, the entire fiber length is scanned. Multiple scans of each fiber are usually performed to improve the temperature measurement quality. As a result, the length of the fiber has an impact on the measurement time (longer fibers require lengthier measurement times). Most DTS equipment permit extending the measurement time to improve the temperature trace.

The DTS system incorporates a computer, either internally or externally, that processes some of the data and mainly provides a means to store the measurements results and pass measurement results to other equipment. Figure 1-2 shows a conceptual configuration of a DTS system.

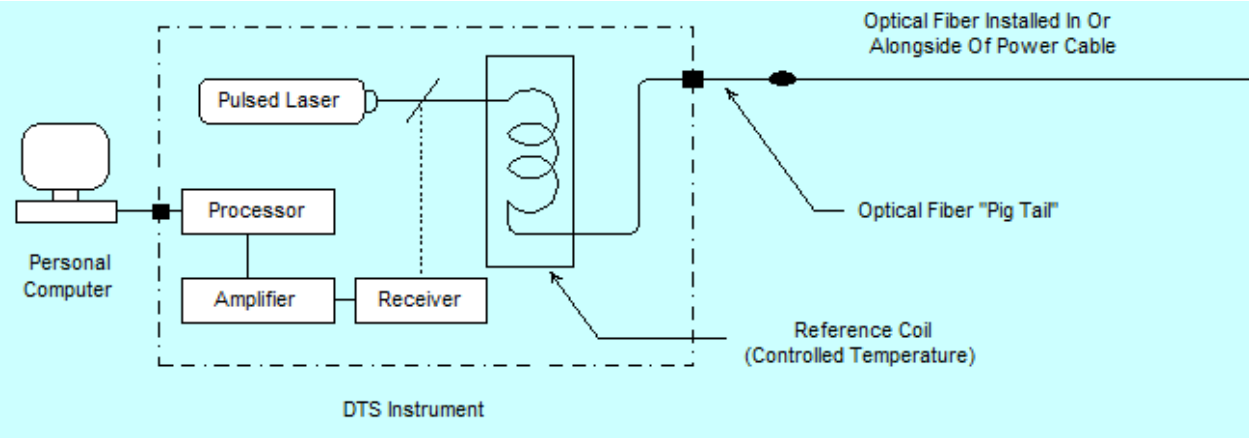


Figure 1-2
Basic configuration of DTS equipment

Most new DTS systems use single-ended measurements where only one end of the DTS fiber is connected to the equipment. These types of systems requires a thorough calibration procedure usually putting some form of known temperature (either using a connected piece of equipment or simply an ice water or boiling water bath) at the near and far ends of the sensor fiber. Some DTS equipment have the ability to enter fiber characteristics but the calibration process is still required.

A few DTS systems use double-ended measurements where a loop of fiber is connected to the DTS equipment. This type of configuration effectively reduces the measurement distance by half but permits some degree of self calibration of the fiber without knowing the specific fiber characteristics.

1.3.4 Types of Optical Fiber Sensors and Fiber Degradation

Two types of optical fiber are available, and both may be used for temperature measurements.

Single Mode Fiber: Single mode fiber is most commonly used for communications purposes. This type of fiber is narrower (as compared to multi-mode) with an approximately 9 micro-meter (µm or micron) glass core diameter. The narrow fiber construction is suited for transferring only

one mode of light but has fewer reflections and, therefore, lower signal loss as compared to multi-mode fiber. For temperature monitoring purposes, the single-mode fiber offers an advantage for measuring temperatures over a much longer distance (30-50km) and might be more appropriately applied to submarine cable installations or locations where a single-mode fiber already exists but retrofitting a multi-mode fiber is not possible. Disadvantages of single-mode systems are that the spatial resolution is 4-10m (meaning that the resulting measurement is an average over this distance) and the temperature resolution is only approximately 2.5C°.

Multimode Fiber: Multimode optical fibers are physically much thicker (50-62.5µm) which allows for multiple modes of light to pass through the fiber and for a greater number of reflections. This greater attenuation (loss) of the signal limits most multimode-based fiber optic systems to 15-18km. However, the increased number of reflections means that temperature measurement systems based on this technology have a better ability to sense temperature. The spatial resolution is about a meter (3ft) or less, and the temperature resolution can be better than 1C°.

For power cable temperature monitoring, most of the systems use multimode technology because of the better overall accuracy and resolution. The length limitation is seldom a major constraint since many underground cable circuits are less than 10miles (15-16km).

Hydrogen Darkening: Glass optical fibers have been used for many years. Some fibers contain compounds based on silica dioxide (SiO_2) which may react with hydrogen atoms in the atmosphere or other locations to form hydroxyl (OH). Hydroxyl can block certain wavelengths of light from passing through glass fibers; this has implications for selecting the laser used in the DTS system. Also, if the DTS system is implemented near the limit of the total allowable signal loss, a degraded (darkened) fiber might limit performance as the fiber ages.

Free hydrogen is generally not available in power cable environments but has been found to affect the use of DTS fiber optic monitoring systems in the petroleum industry. Some cable manufactures use an integrated fiber in a stainless steel tube to prevent damage and exposure to the environment.

2
APPLICATION CONSIDERATIONS FOR DFOTS ON UNDERGROUND POWER CABLES

2.0 Introduction

The successful application of distributed temperature sensing (DTS) or distributed fiber optic temperature sensing (DFOTS) require that consideration be given to several areas as follows:

- Fiber location within the cable trench
- Length of cable to be monitored
- Location of equipment to monitor the fiber
- Connecting and interfacing with monitoring equipment
- Procuring, installation, and commissioning of monitoring system
- Specifying equipment

Considerations for each of these areas are discussed in this section.

2.1 Fiber Location

Cable ampacity is focused on finding the current loading limit so as not to exceed the maximum allowable conductor temperature essentially to avoid damaging the cable insulating material immediately adjacent to the conductor. From this standpoint, temperature monitoring would ideally be situated to monitor the conductor temperature directly. However, because the conductor is energized at high voltage, this is generally impractical except on an experimental basis.[2] Therefore, a location away from the conductor is selected for temperature monitoring purposes. This affects the measurements of cable temperature in two ways:

- **Temperature Interpretation** – Because the measurement location is further away from the conductor - the point of interest - measurements some distance away must be used to infer the temperature of the conductor. This requires interpretation of the measurement results.
- **Thermal Time Constant** – By being some distance away from the conductor that most closely experiences the variation in temperature with changing load, there is a longer thermal time constant associated with the cable heat generating a response in the temperature. The thermal time constant and associated delay in the temperature responses increases with respect to distance away from the conductor (see Figure 2-1).

[2] One utility installed a fiber optic sensor for distributed temperature sensing in the fluid channel of a self-contained fluid-filled cable for a few hundred feet near the terminals of a submarine cable.

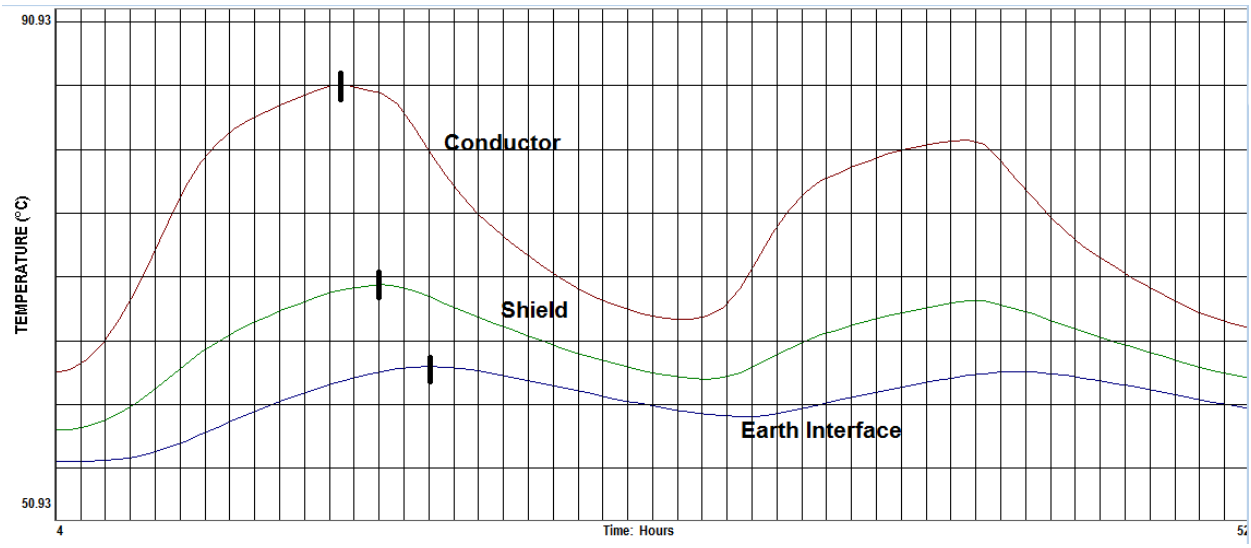


Figure 2-1
Illustration of thermal time constant among the conductor, shield, and earth interface temperatures of a pipe-type cable subjected to a changing load

Selecting the location of the fiber for temperature monitoring depends on many factors, each of which has some advantages and disadvantages that are summarized in the following sections.

2.1.1 Embedded Under Cable Jacket

Placing the fiber optic sensor under the cable jacket, sometimes in place of a concentric neutral wire, locates the fiber as close as practical to the conductor. Since the conductor temperature is ultimately the value of interest, closer proximity to the conductor minimizes both the difference in temperature and the thermal time constant between the conductor and point of measurement. This reduced spacing between the measurement point and the conductor helps correlate the relationship between changing load and conductor temperature. Having the fiber integrated with the power cable also assures that the fiber optic monitoring system will be ready and commissioned at the same time as the power cable, so monitoring of the power cables can occur immediately when the system is put into service.

Often pairs of fibers will be used for each power cable to provide some degree of redundancy. Figure 2-2 shows an example of an integrated optical fiber under the cable metallic sheath.

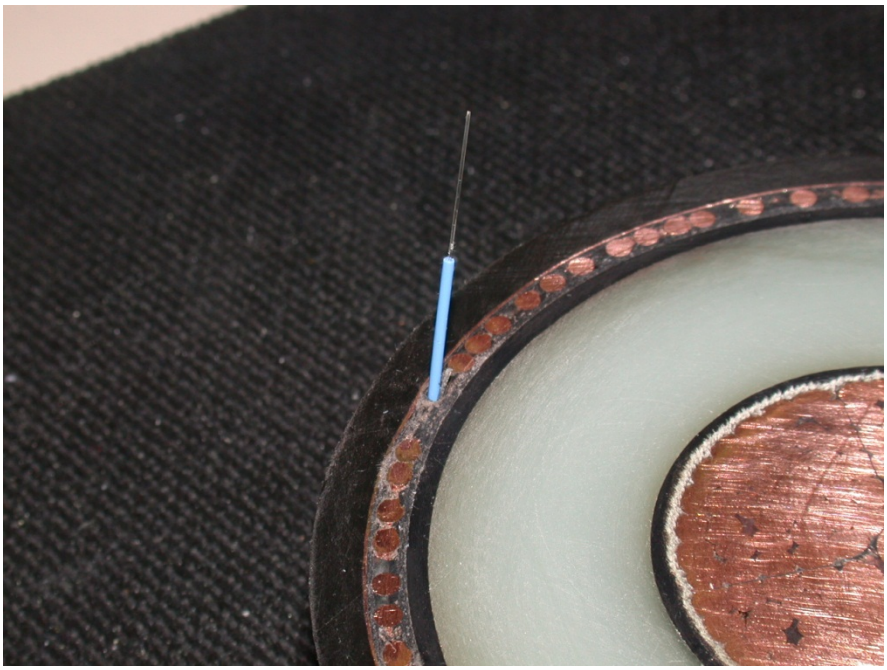


Figure 2-2
Figure showing an integrated optical fiber in a stainless steel tube located in place of a concentric shield wire

However, placing the temperature monitoring fiber in this location has several potential disadvantages:

- **Extruded Only**: This type of application is only suitable for extruded cables. Self-contained cables must place the fiber outside the metallic sheath because of concerns about degrading the fiber if it is exposed to dielectric liquid, and the fiber must, as a minimum, be placed outside the cable pipe coating in pipe-type cables.
- **Varying Position**: The fiber is wrapped helically around the cable usually in place of a metallic shield wire or in a stainless steel or polymer tube below the metallic sheath meaning that its relative position varies along the length of the cable even if all other installation conditions remain constant. This can contribute to difficulty in interpreting the results in measured temperature.
- **Increased Cost**: The cost of adding a fiber to a power cable is $1-3 per foot of power cable (2012); this is comparable or potentially less expensive than procuring a separate, dedicated fiber optic cable. However, the cost of splicing the high-voltage splices increases by 10-15% because the activities of both power cable splicing and fiber splicing must be combined.
- **Combined Jointing Activities for Power and Communications**: If the fiber is integrated into the cable under the jacket, the fiber optic sensor must be installed simultaneously with the power cable including constructing all the splices. Generally, the high-voltage cable splicers are different personnel from the communications fiber splicing that are typically required for fiber splicing. This requires increased coordination for both activities to be done together. The integrated fiber also must be removed from under the cable jacket and connected to a fiber splice point without allowing moisture to enter the power cable.

- **Routing Fiber from Terminations May Be a Challeng**e: With the integrated fiber, the fiber must be routed from the termination to a control building.
- **Possibility for Common Failure**: In the event of a power cable failure, the optical fiber may also be damaged which would affect temperature monitoring on other portions of the cable. If the fiber fails in a particular section, it would be impractical to replace the power cable in order to reconstitute a complete end-to-end fiber. Therefore, the DTS temperature monitoring system will not be operable or, as a minimum, not be monitoring the temperature of that section.
- **More Fiber Splices Required**: Locating the fiber with the power cable means that the fiber optic cable will need to be spliced at every power cable splice.
- **Elevated Temperature Operation**: The upper operating temperature limit for some optical fibers is in the 80-85°C range. If the cable conductor is operating at full rated temperature (90°C for most extruded cables), the cable shield could be operating around the limit of the fiber. The extent of fiber aging is not well defined with respect to high-temperature operation, but it's conceivable that the fiber may have a shorter operating life than the typical 40-year design life of a power cable system.
- **Maintenance of Fiber System**: With the fiber integrated into the power cable, the power cable circuit will generally have to be taken out of service (at least with transmission voltages) in order to enter the manholes to do any maintenance on the fiber optic system if there is a problem.

Generally, the disadvantages related to using an integrated fiber are mostly associated with the installation process. Many transmission cable circuits are operated below their rated temperature, so fiber aging has not yet materialized as an industry problem.

2.1.2 Conduit Occupied with Power Cable(s)

Instead of having the fiber integrated under the cable jacket, a separate fiber optic cable usually consisting of a bundle of fibers (4-6 fibers for redundancy), aramid fibers (or other longitudinal strength member for pulling) and a protective jacket may be installed for the purposes of monitoring temperature. This type of fiber optic cable (see Figure 2-3) can be placed in an occupied conduit as discussed in this section as well as a parallel conduit or attached to the outside of a power cable or pipe (directly buried).

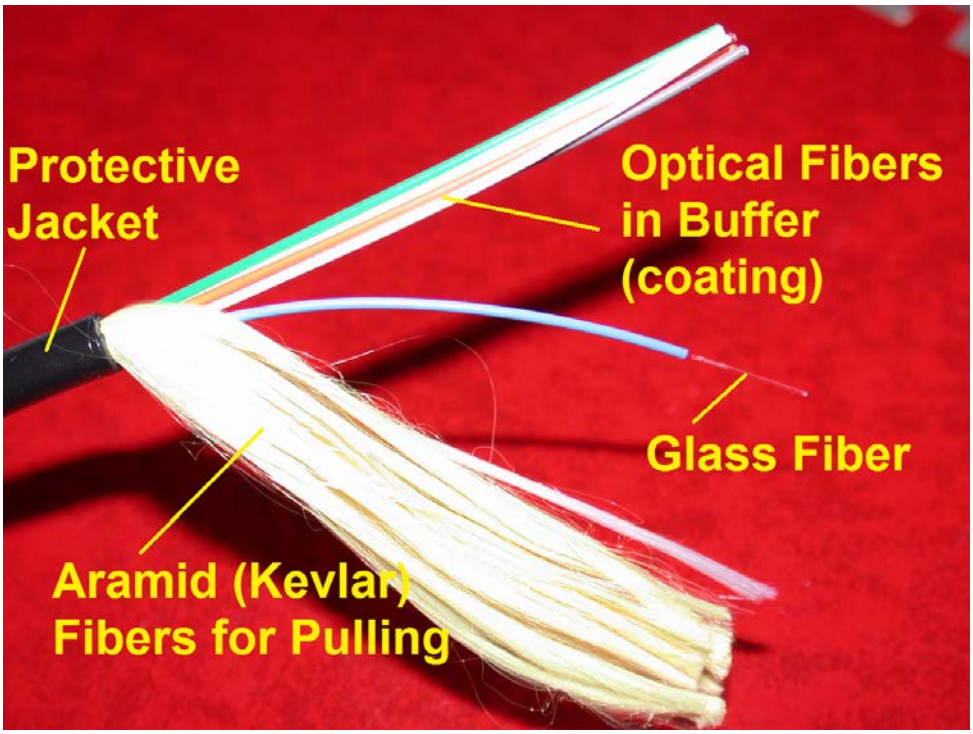


Figure 2-3
Example fiber optic cable for temperature monitoring

Placing the optical fiber in the annular space between the power cable and the conduit is another alternative for monitoring the temperature (see Figure 2-4). This location is most often considered when there are no spare conduits in the duct bank and a fiber must be retrofitted.

The advantages to using a fiber installed in the annular space are that another conduit is not necessary and the temperature measurement location is closer to the cable conductor and potentially in contact with the cable jacket. This type of installation can also be used on extruded or self-contained cables installed in conduits. The fiber optic cable can be retrofit to existing circuits. Also, the fiber optic cable will operate at a lower temperature providing lessening the possibility of aging the fiber.

There are a few disadvantages:

- **Retrofitting the Fiber**: In practice, utilities using this type of fiber placement have experienced difficulties with installing the fiber in an already occupied conduit. Blowing a tag line (i.e., “mule tape”, etc.) through an occupied conduit is more difficult than in an empty conduit. If the fiber cannot be installed end to end, or at least through most manhole-to-manhole areas, the DTS fiber sensor cannot completely monitor the cable. Sometimes the tag line can be installed, but the pulling tension when pulling the fiber optic cable exceeds allowable limits or there is a concern about damaging the jacket of the power cable. The installation issue may or may not be more complicated when putting a fiber into a conduit occupied by multiple (smaller) distribution cables in the same conduit. Difficulty with retrofitting the fiber into an occupied conduit is the reason this approach is seldom used when retrofitting the fiber.

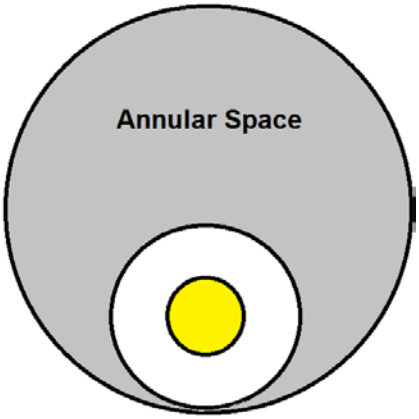


Figure 2-4
Annular space in a conduit

- **Location of Fiber**: After the fiber is installed, there is no specific knowledge of where the fiber is placed along the length of the power cable. It could be partially looped in the air space between the cable and conduit, be wedged between the cable and conduit near the bottom of the conduit or in contact with the outer conduit (but not the cable). This could result in some variability in temperature readings that may make interpreting the resulting temperature more difficult.
- **Probably More Splices**: Since pulling the fiber into occupied conduits may result in greater pulling tensions, it may be necessary to pull fiber along the same lengths as the power cable thereby requiring fiber splices in each manhole.

2.1.3 Parallel Conduit

Installing a separate fiber optic cable (see Figure 2-3) in a parallel conduit to the power cable(s) is probably the most common installation method for DTS system. The advantages include:

- **Retrofit Possibilities**: Since the fiber optic cable is being installed in an empty spare conduit, it may be added to a power cable system that is already installed. The fiber optic sensor cable can be installed both with a new system and older existing system.
- **Uniform Orientation**: By being installed in a parallel conduit, the fiber optic sensor is generally maintains a uniform spacing and orientation to other power cables in the trench. This generally permits easier interpretation of the measurement results.
- **Availability for All System Types**: Using a parallel conduit for the fiber sensor makes this method available for all cable system types (pipe-type, extruded, and self-contained).
- **Separates Power & Communication Contractors**: The power cable installation work can be done separately from the fiber optic cable installation (usually by a telecommunications contractor). By having the power and fiber work separated, it is not necessary to closely coordinate both activities.
- **Fewer Splices**: Pulling fiber through manholes (rather than cutting and splicing) is possible so there will likely be fewer fiber splices required.

The main disadvantages to this approach are:

- **Lower Temperature Correlation**: The fiber sensor is further away from the conductor, so interpreting the results requires a careful evaluation. The difficulty in interpreting the results is further complicated because the impact of one particular power cable (or cable pipe or conduit with occupied cables) has less correlation to the fiber because there is likely some mutual heating influence from multiple sources that must be considered. Interpreting results is also more difficult if the circuit is lightly loaded.
- **Requires a Dedicated Conduit**: Installing the fiber in its own conduit means that some of the infrastructure in the duct bank is unavailable for other uses (telecommunications, etc.). Sometimes this is addressed by putting an inner duct within a larger conduit so that the conduit may be used for other purposes.

2.1.4 Parallel Communications Conduit/Fiber Common to Communications Cable

Using a fiber optic cable that combines communications and temperature monitoring functions is a possibility and allows efficient use of a conduit in which the fiber optic cable is installed. The fiber optic cable typically contains a few tens of single mode fibers for communications and then 2-4 multimode fibers for temperature monitoring. In these configurations, the fiber optic cable will generally be routed outside of the power cable manholes into separate hand holes so that a power cable failure will not interrupt the communications trunk that may be used for system protection and relaying.

This approach to installing a temperature monitoring fiber must consider that the communications and temperature monitoring systems must be specified at the same time. Also, there needs to be coordination for routing the temperature monitoring fibers and communications fibers within the substation(s) which may need to be located at different terminal points within the connected control rooms.

2.2 Distance to be Monitored/Selection of Equipment Range

Generally, the distributed temperature monitoring system will seek to provide monitoring for the entire underground cable circuit. DTS monitoring systems are available with a maximum measurement range. Some of the suppliers have equipment available with varying maximum range capabilities; usually, the equipment with a higher range limit will also have increased cost. Essentially, the equipment with longer range capabilities use a more power and expensive laser.

When selecting equipment, it is important to consider that the range limit provided by suppliers is only an estimate. The real factor to consider is the “optical budget” of signal loss that the equipment can tolerate and still obtain useful temperature measurements. Fiber has some natural attenuation to the light signals. This varies by fiber type and the wavelength of light. Splices in the fiber also introduce losses that consume a portion of the optical budget. Some typical values for fiber and connector losses are listed in Table 2-1. The consideration for selecting DTS equipment in regards to the range of the equipment should be the expectations about the total dB losses for the system.

Table 2-1
Typical Fiber and Connector Signal Loss Characteristics

Parameter	Signal Loss[3]	
	850nm	1300nm
50-62.5µm Multimode Fiber	3.5dB/km	1.5dB/km
Mechanical Splice/Connector	0.20-0.75dB	
Fusion Splice	0.10-0.3dB	

For example, if a system is quoted as having a range of 15,000m, it is effectively saying that it has a total allowable signal loss of approximately (15.0 x 2dB =) 30dB of allowable signal loss for a hypothetical 9.3mile circuit. If there are splices every 1,000m (3,300ft) This maximum circuit length is reduced due to up to (14 splices x 0.25 dB/fusion splice =) 3.5dB of signal loss from splices, which reduces the allowable length to 8.2miles. For general guidance, 85-90% of the DTS equipment supplier's maximum equipment range should be used when sizing equipment for a particular cable circuit.

As a minimum, there will be a fusion splice to connect the optical fiber integrated in the power cable or separately in a fiber optic cable to the special pigtail connector used for connection to the DTS equipment. Most of the DTS equipment uses an angle polished connector (APC) as shown in Figure 2-5 (often, the correct connector is green in color). There will likely be a couple of fusion splices introduced between the end of the power cable (possibly the last hand hole or manhole) and fiber that runs the bulk of the distance to the control room where DTS equipment may be located.

Selecting a location to place the DTS equipment is discussed in a later section of this report. This is a factor when selecting the range capability of equipment.



Figure 2-5
Example angle polished connector used for DTS measurements

[3] Based on values published by the Telecommunications Industry Association (TIA) Standard 568.

2.3 Locating DTS Equipment (Portable vs. Permanent)

DTS equipment can be placed permanently in a substation or used as a portable unit. The following sections provides characteristics for each type of system.

2.3.1 Permanent Installations

Most DTS systems are installed permanently in a substation control room and are dedicated to a particular circuit or set of circuits.

There are several reasons for this permanent installation configuration:

- **Equipment Environmental Restrictions**: Most DTS equipment has a limited ambient operating temperature in the range of 5-30°C. There is a reference coil within DTS equipment cabinet (see Figure 1-2) that has to be maintained with a certain temperature range. The cooling fans and heaters within the DTS equipment are constrained by the extent of how much they can adjust for the outside ambient air temperature.
- **Protection from Weather**: The DTS equipment is not field-hardened so it cannot be exposed to moisture.
- **Security**: While the electronics have limited value in general, they may have perceived value to non-utility personnel or could be the subject of vandalism. Therefore, having the DTS equipment located outside of a secure substation building or control room should generally be avoided.
- **Mechanical Handling**: Some components of DTS equipment require careful alignment, so frequent moving or handling may reduce the performance of the system. Permanent installations avoid the movement, drops and vibration often associated with taking this sensitive equipment into the field.
- **Connection to Network**: The utility often wants to disseminate measurement results to engineering and operations within the utility. Therefore, the DTS equipment needs to be located where there is a convenient SCADA or other network connect which is generally within a substation control room.
- **Interface with Real-Time Ratings**: Similar to the network connect, some DTS equipment is connected to real-time rating systems, which are often run on computers within the substation or at the operations center. So even if the DTS equipment is field-hardened, the computer running the rating software may not be suitable for that environment.

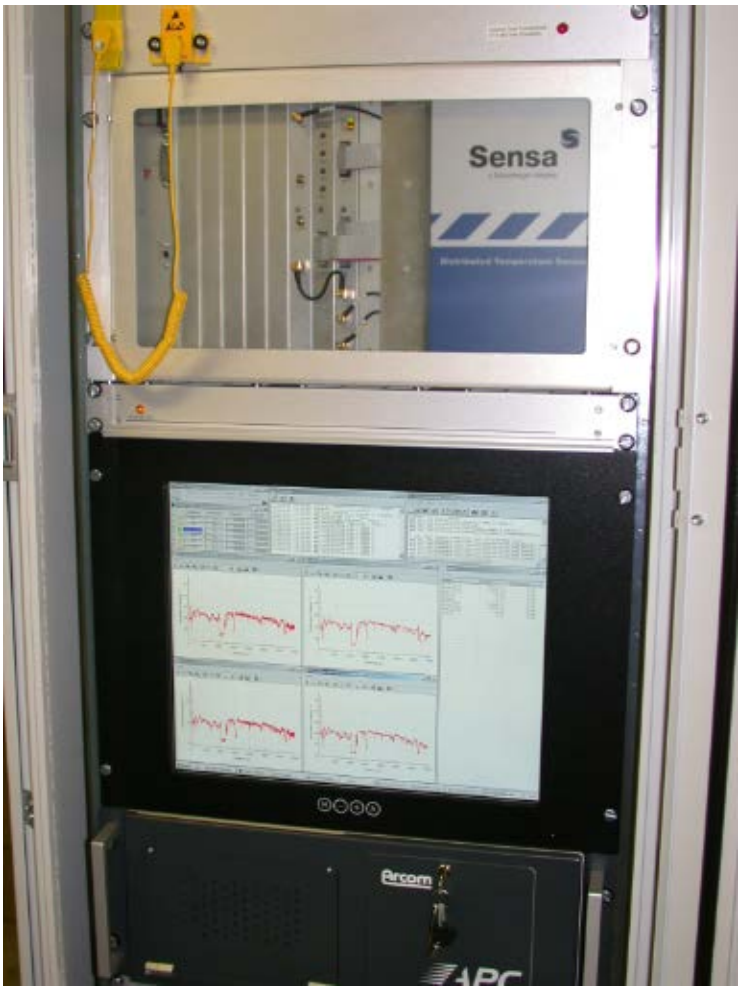


Figure 2-6
Example of rack-mounted DTS system in a substation

The location of the DTS equipment also is a consideration for selecting the fiber sensor range. For example, if the equipment has a range of 10km (~6 miles), and the circuit is 10 miles long, there are two approaches that could be used:

- **One DTS System**: A single DTS system could be installed if there is a suitable central location to install the equipment and have the DTS equipment scan fibers in both directions.
- **Two DTS Systems**: Use two DTS systems located at both terminals and have each system scan half of the cable circuit.

DTS equipment can generally be equipped with multiple ports to monitor multiple fibers. This may be used to monitor each phase of a cable system (in multiples of 3) or multiple circuits that all connect to a common substation. Some DTS equipment suppliers also have optional multiplexers that handle the switching of the DTS equipment among multiple fibers.

2.3.2 Portable Measurement Equipment

DTS equipment can be used on a temporary (portable) basis to monitor cable temperature for a finite period of time ("spot" measurements of less than an hour, or extended measurements of a few days to a few weeks).

Use of portable equipment is sometimes considered for situations where the cable circuit is not initially loaded up to full rated load for a period of time or possibly only on an intermittent basis so the utility does not feel continuous monitoring is necessary. Some utilities also have installed DTS fibers in multiple locations but not instrumented the lines with the electronics.

Using DTS equipment on a portable basis still requires that the equipment be placed in an environment suitable for the equipment to operate. This means both maintaining the acceptable operating temperature of the equipment and protecting the equipment from weather. Figure 2-7 shows a DTS test instrument installed in a dry cable tunnel to monitor pipe-type cable temperatures, and Figure 2-8 shows a portable DTS unit operated from the back of a vehicle for field measurements.

Most DTS equipment must be connected to some type of computer to configure the equipment. If the configurations functions are managed by an external computer, a portable computer of some type can be used. If the DTS equipment includes an integrated computer, usually some type of external monitor, keyboard and mouse may be needed to run the configuration software.

A key difference of using DTS equipment in a portable mode is that the utility engineer must very familiar with the configuration functions needed with the system. The functions that must be understood to use the equipment in portable mode include:

- Training
- Connection of the equipment to the fibers
- Configure the DTS equipment for different types of fiber
- Start and stop measurements
- Store and extract data
- Determine the portions of the fiber that should be monitored
- Calibrate the DTS equipment relative to a reference temperature at accessible locations along the cable system
- Basic troubleshooting if there are issues with the equipment

The considerations listed above are generally not necessary when the DTS equipment is permanently installed because the supplier or contractor providing the equipment will perform all of these activities as part of the purchase agreement.



Figure 2-7
EPRI's portable DTS equipment monitoring pipe-type cable temperatures in a tunnel



Figure 2-8
Early version of EPRI's portable DTS equipment operated from the back of a van

2.4 Telemetry Considerations

After the DTS equipment obtains measured temperatures, the data must be accessed.[4] This involves moving the data from the DTS system to another platform. The options that exist are listed below:

- **Retain on DTS Computer**: In the simplest form, the DTS measurements could be retained only on the DTS computer. This might be done in situations where the cable circuit is lightly loaded (well below rated load) such that the measured values are not of much interest. During a period of high load, utility personnel can go to the DTS system and obtain data when needed.
- **Download**: A utility procedure could be developed where data is regularly downloaded to a solid state device or CD for archive purposes or for analysis. Regardless of the use, the utility must carefully monitor the storage space on the DTS computer so that the space does not get depleted. Periodically, the files need to be purged from the DTS system for it to continue to operate and archive data.
- **Use a Remote PC Access Program**: Some utilities permit remote terminal access to the DTS computer. However, this often requires access through a secure network connection. By accessing the DTS system in this way, the data can be downloaded without directly visiting the substation or control room but is otherwise no different than directly downloaded the data.
- **Network Connection**: The DTS computer could be directly connected to the utility network like any other computer on the system. The hard drive might be shared out so that remote access is possible.
- **SCADA**: DTS measurements results could be sent over the utility's SCADA system. However bandwidth considerations may limit the ability for the data to be transferred this way. A further discussion of this approach is provided in Section 2.6.2.

2.5 Security and Interfacing with SCADA and EMS

One of the challenges of using DTS systems is that the computer system that is used with the DTS equipment probably has some proprietary components and may have been selected because of requirements of the system. As a result, it may not be a standard computer that is obtained from the utility's information technology (IT) department and, as a result, may not have the clearance to directly connect to the utility's network.

Implementing DTS on the cable circuit will require that the utility IT department evaluate the computer associated with the DTS system. However, this is often impractical because there usually is not any flexibility in altering the computer system if it is not in compliance with utility security protocols. If the computer can be accepted without modification, data from the DTS system can be distributed more readily to the utility departments seeking to use it.

[4] In the context of this discussion, the report discusses the options for obtaining data from a permanently installed DTS system. Obtaining data from a portable DTS system is dependent on the device and will vary by equipment manufacturer.

The other alternative is to have the DTS computer remain outside of the network but have a network connection through SCADA via an accepted protocol (MODBUS, DNP3, IEC 60870-5-101, etc.). Some DTS equipment vendors only support one type of protocol so compatibility should be investigated prior to selecting a supplier.

2.6 Procurement, Configuration, and Commissioning

Procurement of a DTS system generally requires developing a specification (see Section 2.6.1) and procuring the system. In general, the DTS equipment suppliers do not do the fiber installation work and may not have the specific knowledge or background about high-voltage power cable systems. If the DTS system is being supplied as part of a larger turn-key cable project, the prime contractor will be working with a local telecommunications contractor to install the fiber and perform the fiber splicing. If the utility is procuring the DTS system directly, the installation of the fiber would either be done by the utility's telecommunications group or an outside contractor that can perform the fiber installation and fusion splicing.

2.6.1 General Specification Requirements for DFOTS Systems

The DTS system requires two main components; DTS electronics to measure the temperature and the installed optical fiber. The requirements for each are summarized below. The reader is reminded that the DTS system and fiber must be compatible and specified together, but there may be instances where the fiber is procured initially and the electronics are not obtained until months or years after the cable system is already in operation.

- **Fiber** – Multimode fiber is generally the preferred fiber type for the most effective DTS measurements on an underground cable system. A 50µm (micron) graded index fiber with a 125µm buffer is commonly used. Table 2-1 lists industry-standard parameters for the fiber although it is desirable to specify more stringent requirements for the fiber (attenuation of 2.4dB/km at 850nm/0.6dB/km at 1300nm).

  The fiber can be obtained with "loose tube" or "tight buffer". The loose tube design is usually applied for installations that will result in more rigorous mechanical stresses on the fiber during handling or installation. In either case, the fibers should be color coded so that multiple fibers can easily be identified.

  As already discussed, the fiber optic cable used for distributed temperature sensing should have some type of strength member (Aramid fibers). The cable should be jacketed with a material that is compatible with the installation environment and provide mechanical protection (high-density polyethylene, polyvinyl chloride, or polypropylene are used).

  Fiber lengths should be specified as continuous. If multiple cut lengths are required for a particular project, the procurement specification should identify the cut lengths that are consistent with the pulling section lengths.

  The installation of the DTS fiber should be consistent with local utility practice for communications systems (i.e., NECA/FOA 301-2004, "Standard for Installing and Testing Fiber Optic Cables", etc.). The utility should prepare drawings that show the route and conduit or other location where the fiber should be installed.

- **DTS System** – The utility should identify the basic requirements for the DTS system including identifying the number of cables to be monitored and the installed power cable lengths.

  Mechanical details about placement of the DTS system within the control building including the space available for rack-mounted equipment. If a portable DTS system is being purchased, the utility should specify the type of case that is desired and designate a minimum mechanical shock that the equipment must withstand before damage occurs.

  If the utility wants the DTS manufacturer to supply the cabinet, computer (if needed), uninterruptable power supply or other equipment, this should be outlines in the specification.

  The DTS equipment supplier should provide special connectors needed to connect the fibers to the DTS system.

  Some standard information should be requested to aid the utility in evaluating and comparing bids. This information should include:
  - Type of connectors for DTS equipment
  - Data sheet on fiber splice enclosures
  - Allowable DTS equipment attenuation
  - Accuracy of DTS equipment being supplied
  - Spatial resolution of DTS equipment being supplied
  - Number of DTS units to be supplied to meeting project requirements
  - Design mean time before failure (MTBF) for the DTS equipment
  - Duration of equipment warranty
  - Experience summary of systems supplied
  - Suggested spare parts list
  - Operating instructions, including calibration procedures
  - Operating environment and power requirements for all equipment
  - Supported SCADA protocols
  - Number and limitations (if any) of configurable temperature reporting zones

2.6.2 Configuration of DFOTS/Zone Definitions

Distributed temperature measurement systems generate a tremendous amount of data. These systems generally provide a temperature measurement each meter along the cable route, and some systems monitor multiple cable phases. For example, a 5-mile extruded cable system with all three phases monitored would generate more than 24,000 values each time the DTS system performs a measurement. Considering that the equipment could perform measurements once every 10-30 minutes; the result is a lot of data.

Most utilities utilize some form of SCADA or PI Historian system to store data points on the utility system. These data points may consist of measured load data on a cable circuit or possibly weather data such as wind speed or air temperature in a given area or possibly ambient soil

temperature. The relatively limited bandwidth of most utility SCADA systems can accommodate these small quantities of data. However, it would be difficult to transfer 24,000 values that possibly amount to a few hundred kilobytes of data. Plus, the SCADA system would need to store all of these values.

For this reason, many DTS systems are configured with zones that monitor a range of distance along the cable route and report only one or two values for the entire zone (perhaps a maximum and average temperature). In this way, a few tens of numbers, rather than thousands of values, need to be transferred over the utility SCADA system. This is more manageable in terms of SCADA storage space and defining registers on the SCADA system for the data.

Selecting the zones is done by reviewing the plan and profile drawings or after performing an initial temperature measurement to evaluate areas of interest along the route. Some basic suggestions for defining zones are listed here:

- **Spacing Between Major Accessories**: As a minimum, zones may be defined between adjacent manholes or between manholes and the terminations. This provides end-to-end coverage of the circuit with a minimal amount of detail.
- **Unique Duct Bank/Trench Configurations**: In locations where the cable trench has unique characteristics, it may be desirable to define a zone just in this area. For example, if the cables are placed in a configuration with reduced spacing or different backfill or native soil characteristics, these areas may be of interest.
- **Trenchless Installation Sections/Unusually Deep Sections**: Especially deep locations or those installed in casings that may have warmer (or possibly cooler) operating temperatures should be modeled.
- **Route Sections in Close Proximity to Parallel Circuits/Heat Sources**: Locations in close proximity to other circuits that could be hot spots should be monitored.
- **Route Sections Crossing Other Utilities**: Locations where the cable circuit crosses other utilities, often at road intersections, should be monitored.
- **Tunnel Sections**: Though usually cooler than conventional buried sections, tunnel installations should be monitored to verify that an unusual condition does not exist in the tunnel that may be causing higher-than-expected temperatures on the cables.
- **Ambient Soil Zones**: If the optical fiber cable will be run through an area that is sufficiently remote from other underground heat-producing sources, the DTS fiber can also be used to measure the ambient soil temperature which is an input parameter to off-line ampacity programs as well as real-time rating systems.
- **End-to-End**: Depending on the system, it may be possible to define a single zone that looks at the maximum temperature along the entire route length. This would provide a cursory indication of the presence of a hot spot and might be used as an alarm point for operations. A subsequent investigation would be needed to ascertain the details about the hot spot, but at least there would be a basic configuration that the hot spot exists.

The ultimate goal of defining zones is to be sure to capture the hot spot along the cable circuit that would represent the limiting point for ratings while minimizing the number of data points that must be transferred to SCADA registers.

With zones defined on the DTS system, the maximum temperature of each zone would be relayed to SCADA, but the full DTS traces would typically still be stored on the DTS computer.

2.6.3 Measurement Frequency

Because power cables, particularly high-voltage power cables, have a very long time constant, temperatures do not change rapidly with changes in load. Therefore, DTS measurements on cable systems can practically be done once every 15-30 minutes and still produce useful results in many cases. Most utilities select measurement times of 5-30 minutes, although the length of the fiber and number of fibers impacts the measurement time.

For example, if there are six fibers being scanned (say two 3-phase circuits, so 6 cables) and 5 minutes is required by the DTS equipment to scan and process each fiber for a temperature measurement, the frequency of measurements will end up being once every 30 minutes.

Aside from the slow thermal time constant of power cables, DTS equipment is generally not suitable for fault location or detecting other rapidly developing conditions due to the long measurement time. However, if the fiber sensor is embedded in the cable jacket and the fault damages the fiber, the DTS system will likely detect the fiber break and may even be able to determine the distance into the fiber where the break occurred.

2.6.4 Commissioning

The temperature monitoring system should undergo a detailed commissioning process. Commissioning usually involves the DTS equipment supplier's representative(s) installing the DTS electronics package (or directing utility personnel on the setup), connecting the fibers and then configuring the equipment to properly measure temperatures from the fibers. A calibration process is important so that the DTS system will accurately measure temperatures. Utility personnel should be trained on these procedures, although in practice most utilities rely on the equipment suppliers to configure the system.

As mentioned earlier, some components of the DTS electronics are susceptible to mechanical misalignment, including that which may occur in the process of shipping equipment from the factory to the installation site. The commissioning process should be able to verify that the equipment is still within factory parameters.

The commissioning process should also include configuration zones and verifying that any SCADA registers are correctly being populated by the DTS system.

Training should be provided to utility personnel. This training should include basic troubleshooting for the DTS system, including if local power is lost to the DTS system and must be re-started.

2.6.5 Reliability, Maintenance, and System Life

DTS equipment for the most part is a passive device. The laser cycles on and off and processing is performed. The only mechanical aspect to a DTS unit is where multiple fiber channels are used. There is generally only one laser within the unit, so the laser must be aligned using an optical switch or multiplexer that, over time, may lose alignment. The laser itself could possibly

become out of alignment due to temperature fluctuations or other factors (vibration, mechanical movement of the equipment, etc.). Alignment issues are more common if the DTS equipment is used in a mobile mode for field tests.

Maintenance of DTS equipment is similar to any other computer equipment and includes maintaining an acceptable operating environment and limiting exposure to dust, insuring that any cooling fans are functioning properly and there is adequate ventilation, etc. A periodic check of the DTS equipment accuracy should be performed.

Perhaps the most routine maintenance for DTS equipment is to monitor available hard drive disk space. DTS temperature traces can each be a few hundred kilobytes of data and are generated often (once every 5-20 minutes). As a result, hard drive space can be depleted quickly which may cause the DTS system to shut down. Software may be available to periodically purge the oldest DTS trace files. An additional consideration is if the computer that is logging DTS data is also used for other purposes (real time ratings, other energy management systems, etc.) where there may be competing uses for available space.

The mean time before failure (MTBF) for the laser units is often quoted in thousands of hours. However, a failure (or other issue) of a component within the DTS system may happen once every 3-5 years based on a small sampling of utilities that have these systems. One DTS manufacturer reported that the design life of their equipment is 7-10 years, while another indicated 28 years. There are no user-serviceable parts within the DTS equipment cabinets, so the units are typically serviced by the manufacturer on site, or the devices are sent back to the manufacturer for service.

2.7 Implementation Costs

At the time this report was prepared, the following represent some of the major cost considerations for implementing a DTS system:

- **Optical Fiber Material Cost**: The optical fibers, whether incorporated into the power cable under the jacket or in a separate, dedicated fiber optic cable will cost approximately US$1.50 to US$4/linear foot. Embedding the fiber under the cable jacket is on the lower range of this cost but increases the high voltage cable splicing costs because of the added effort for coordination, etc. A dedicated optical cable with 4-6 fibers is on the upper range of this cost. As an example, a 5-mile circuit would require about US$40-50k in fiber costs.
- **Optical Fiber Installation Cost**: This cost varies by region, but is typically a few dollars per foot assuming that the conduit is already in place. There is an added cost for fusion splicing the fibers. Fiber installation work is commonly available because it is used extensively in the telecommunication industry. The cost for installation would typically be US$20-30k.

- **Network Infrastructure Cost**: There is a cost associated with configuring the utility network to accept the DTS-generated data, configure SCADA registers, store the data, etc. Usually, this activity is performed by the utility's own technician or network engineer, so the cost is internal to the utility.
- **DTS Equipment Costs**: The DTS electronics is the single most-costly piece of equipment for a DTS system. The range of costs varies from manufacturer to manufacturer and based on the features. For example, the DTS equipment may have as few as one channel or up to 16 channels (each channel being a monitored fiber), may include a multiplexer to switch among connected fibers, include calibration equipment, and have options for communications protocols. The length of fiber that may be monitored affects the system cost as well (monitoring longer fibers requires a more powerful and costly laser). The range of equipment costs is US$35k-150k, with the more expensive devices having longer measurement ranges and a greater number of channels. There may be a need to purchase more than one device, in which case the cost could potentially be doubled.

Based on the above, the basic cost for implementing a complete DTS system for a power cable circuit would start at approximately US$250k in 2012. This gross cost estimate would be subject to local contractor costs and escalation factors for construction constraints (restrictions on allowable work hours, etc.) relevant for a specific project.

3
INTERPRETING DFOTS MEASUREMENTS

3.0 Introduction

Regardless of the equipment that is selected to perform DTS measurements or the type of configuration that is used to get measured results out of the temperature monitoring systems, the value of performing the measurements is to determine if the cable system is operating within accepted temperature limits and to optimize the ratings on the circuits to obtain the maximum capability from the system.

This section of the report discusses the basic functions needed to interpret DTS measurements that have been performed on cable circuits. The reader is expected to have good familiarity with cable ratings and ampacity calculations. The types of analyses discussed in this section would also benefit from having access to a cable ampacity program such as EPRI's Underground Transmission Workstation.

3.1 Resolving Fiber and Cable Installation Distances

One of the fundamental tasks for evaluating DTS measurements is to correlate fiber optic distances with physical locations along the cable route. This often requires some good knowledge of the cable system layout and the routing of the DTS sensor fiber along the route and to the measurement equipment. For example, there are often additional links of fiber optic cable running from the power cable trench to the control building. This can occur if the fiber is integrated under the cable jacket or in a separate fiber optic cable running in parallel to the power cable. While the power cables will run to the high voltage terminal structures, the fiber optic cables and any lengths of pigtails will generally connect into a substation control building. Therefore, the first several tens to hundreds of fiber distance will not be measuring cable temperatures; these will be the fiber temperature remote from the heat-producing power cables (possibly this could be used for ambient soil temperature). The important consideration is that fiber footage "0" does not correspond to the power cable stationing "Sta. 0+00"; the DTS fiber will generally be longer than the power cable. Figure 3-1 illustrates an example.

One strategy to help manage aligning fiber distance with power cable distance is to record the footage markers entering and leaving each manhole. The footage markers are generally printed or embossed on the jacket of the fiber optic cable. DTS sensing fiber may be looped around the walls of the manhole or simply coiled on the side of the manhole either to capture the air temperature in the manhole or to provide some spare fiber in the event the fiber needs to be cut and spliced.

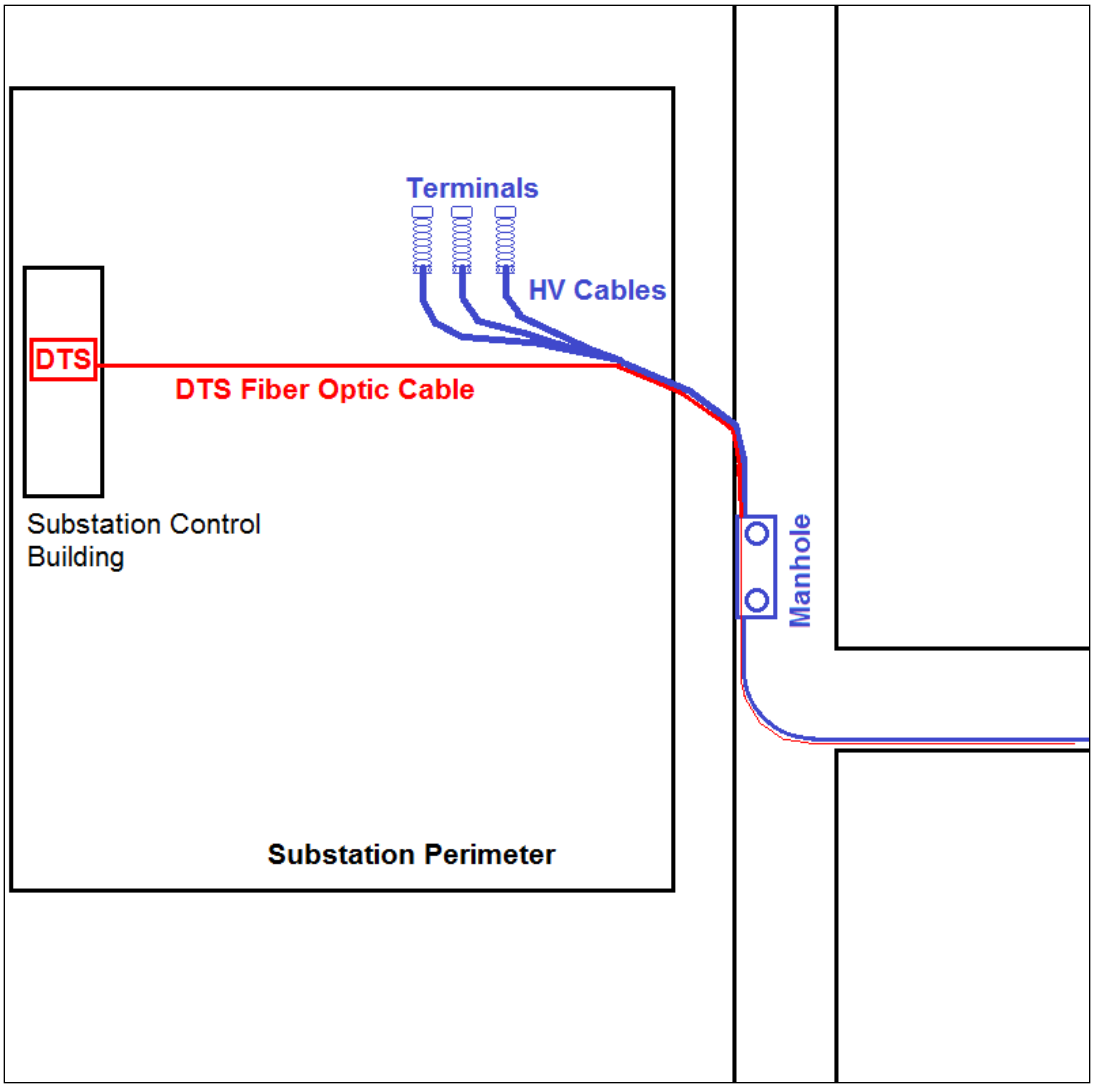


Figure 3-1
Conceptual layout of power cables and DTS fiber within a substation

Another consideration for correlating fiber distance and cable distance specifically affects DTS fibers that are integrated in the power cable under the jacket. Because the fiber is helically wrapped near the outer surface of the cable, the fiber length is 2-6% longer than the cable footage length. When trying to align a measured temperature with a specific location along the fiber, this difference in distance results in some "drift" of the temperature. For example, on a 5 mile circuit, the length difference at the far end of the circuit could be almost 800ft.

As part of the fiber installation process, the telecommunications contractor will perform an optical signal loss test on the fiber. The test will show losses in the fiber after it's installed. Fiber has a typical attenuation that will gradually decay, but more significant drops in signal will show up at major discontinuities that often are associated with fiber fusion splices. Fiber splice locations are associated with splicing fibers in manholes, so the optical loss trace provides a

reference for aligning the fiber length with the physical length of the cable route. An example optical signal loss trace is shown in Figure 3-2. The mechanical connection where the angle polished connector attaches to the back of the DTS system gives a more significant signal loss as compared to the fusion splices over the remainder of the fiber.

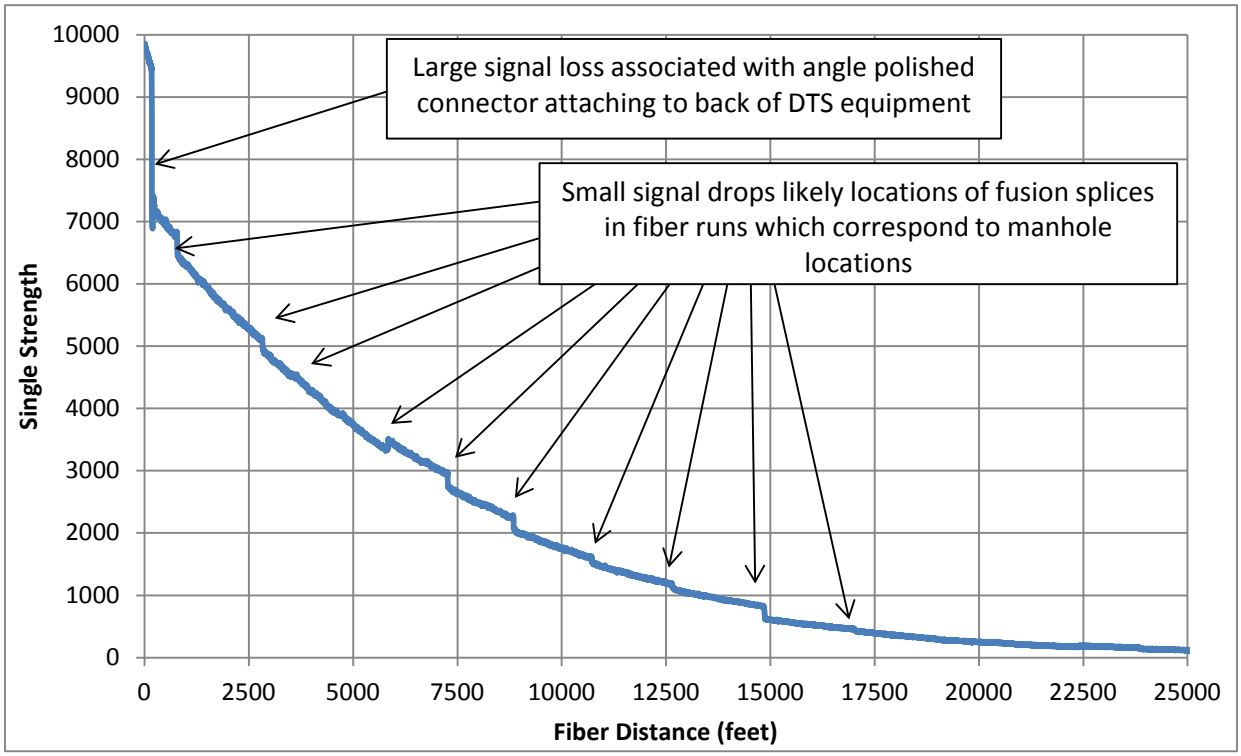


Figure 3-2
Example signal loss trace test result on an optical fiber

Correlating the fiber distance with the installed cable distance can also involve looking for "land marks". Land marks can include anomalies in the DTS temperature traces that appear out of line with the bulk of the measurements results. This evaluation of these anomalies is discussed further in the next section.

3.2 Evaluating and Interpreting Temperature Anomalies

The most challenging part of using DTS measurements is to evaluate the anomalies that are observed in the resulting temperature traces. When using a DTS system on a portable basis, this generally must be done each time the system is used. Otherwise, this step is important when a permanent DTS system is first configured or any time a previously unobserved deviation in the normal temperature trace is recorded.

Generally, interpreting the anomalies involves first aligning the cable length with areas along the temperature trace as discussed in the previous section. Then features of the temperature trace that stand out need to be evaluated relative to locations along the plan and profile drawings. Figure 3-3 shows an example of a DTS temperature trace with some positive spikes in the temperature at various locations (the large spike on the left of the graph is the reference coil within the DTS unit that, in this particular case, operates at approximately 40°C). The small

boxes on the graph show locations of fiber splices, and the unusual features of the DTS trace have been labeled (A, B, C, etc.). One of the temperature spikes ("A") has been investigated and found to align where a pipe-type cable crosses the cable duct bank. This analysis process would be completed for every anomaly observed.

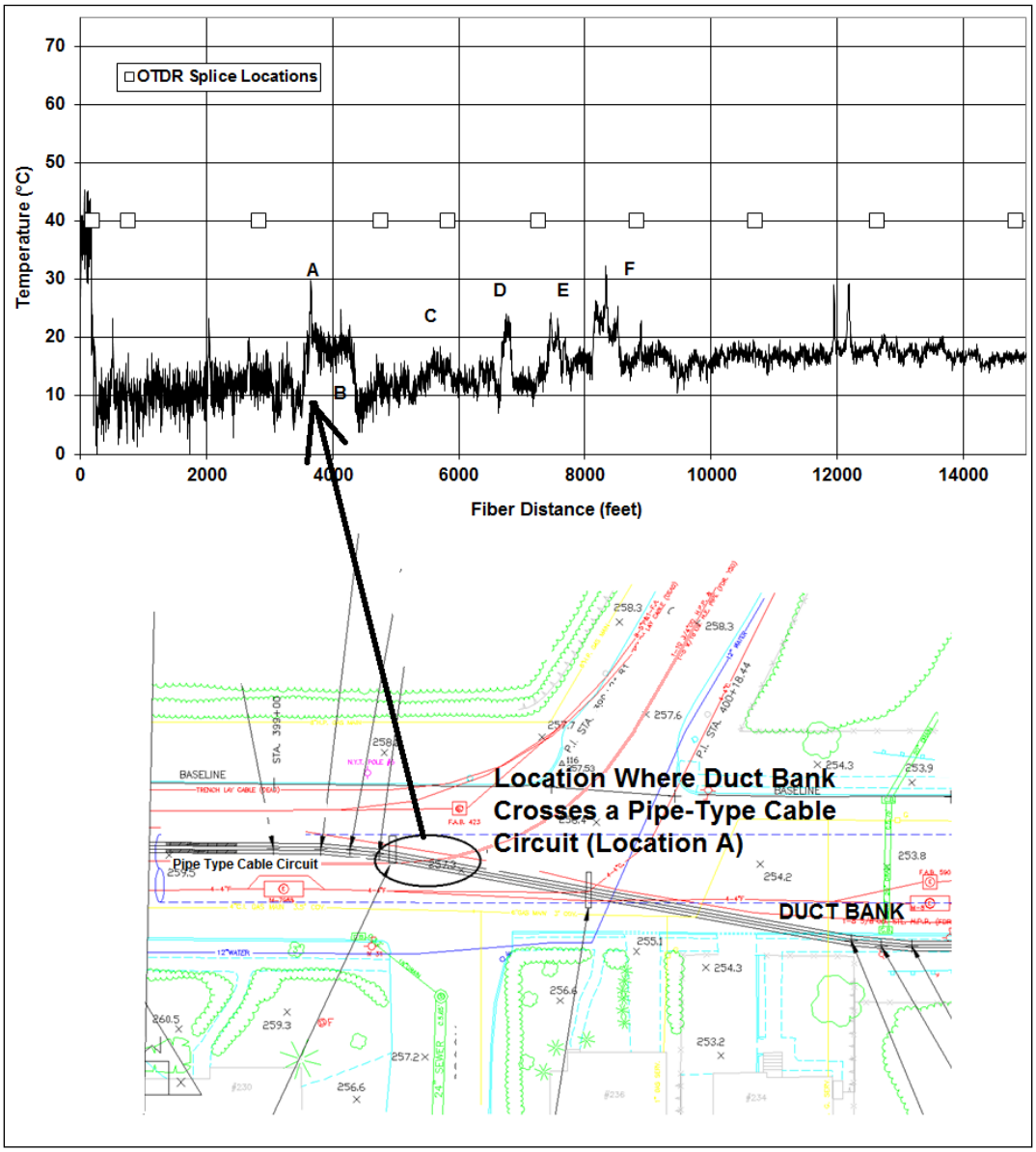


Figure 3-3
Example of correlating a hot spot anomaly with plan and profile drawings

A temperature anomaly can occur for any number of reasons, which are summarized in the following table:

Table 3-1
Summary of DTS Temperature Trace Anomalies and Possible Causes

Type of Anomaly	Considerations for Type of Anomaly	
	Summer: Ambient Soil Temperature is Warm	**Winter: Ambient Soil Temperature is Cool**
Sanitary Sewer Line	During summer months, a sanitary sewer may be indistinguishable from the prevailing ambient temperature or could be slightly cooler	During winter months, the sewage will probably be warmer than the ambient soil temperature and may show up as a hot spot
Water Line	During summer months, the water line may appear as a cool spot as it absorbs heat from the surroundings	During winter months, a water line may be indistinguishable from the ambient soil though it could be slightly warmer or cooler
Storm Sewer	During summer months, storm sewers will probably be indistinguishable from the native soil	During winter months, the storm sewer may appear as a cold spot because it has access to the colder air temperature
Gas Line	Indistinguishable from ambient	
Steam Line	May be warmer than ambient soil but generally less often in service in summer months	Much warmer than prevailing ambient temperature
Power Cable Duct Bank or Pipe-type Cable in Parallel	Depends on conditions but will generally be a hot spot if duct bank/pipe cable is carrying more than 30% of load. An area of elevated temperature may be observed.	
Power Cable Duct Bank or Pipe-type Cable Crossing	Depends on conditions but will generally be a hot spot if duct bank/pipe cable is carrying more than 30% of load. Appears as a spike in temperature trace.	
Manhole/Splice Chamber	Generally cooler, with elevated temperature on either side because of increased burial depth. Fiber looped in manhole will show up as 20-50ft of cooler zone on temperature trace than ambient, especially when cables are loaded about 30%	May be indistinguishable from ambient soil temperature unless covers are open in which case may be cooler if ambient air is cooler
Deep (HDD, Pipe Jacking) Installation Section	Probably a cooler area due to lower ambient soil temperature, possible location in water table and better soil thermal characteristics	
Installation Below Asphalt >4ft	Nominal ambient temperature	
Installation Below Asphalt <4ft	Elevated by 3-5C° over areas covered with vegetation	

3.3 Effective Soil Thermal Resistivity and Inferred Temperature

In a cable rating calculation, the physical makeup of the cable, conduit and/or cable pipe are well understood. Material characteristics and physical dimensions are well defined from industry standards and the manufacturer's cut sheet. However, the soil characteristics are least understood in the cable system and represent about two thirds of the thermal resistance between the conductor and ambient earth. Figure 3-4 shows an equivalent thermal circuit that is used in ampacity calculations (such as DTCR and UTWorkstation); the earth portion on the right is the least understood parameter in the calculations.

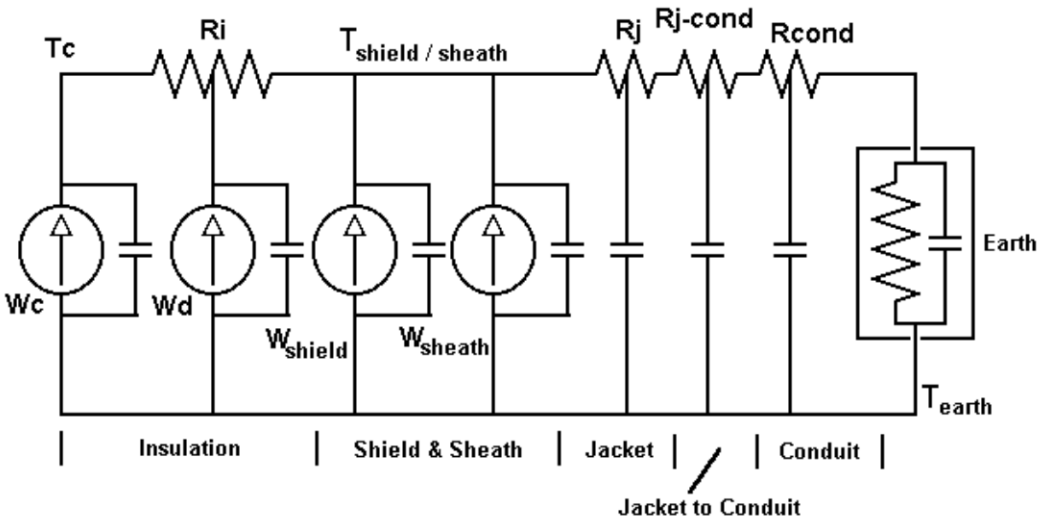


Figure 3-4
Equivalent thermal circuit used to model XLPE cables in conduit

Because of this uncertainty, soil thermal resistivity measurements are often done during the design process and sometimes later to after the cable system is in service. Despite these efforts, soil tests usually only capture a small percentage of the soil characteristics along the line (perhaps once every 500ft to 2,000ft). More information would be helpful to verity ampacity.

As a brief background, soil thermal resistivity tests are typically done using a 1cm diameter thermal probe that is 10-20cm in length that contains a distributed heat source. A thermistor at the center of the probe measures temperature with respect to time after the heat source is powered on. The slope of the temperature-time curve is proportional to thermal resistivity and is the value reported on test reports. A similar approach to measuring thermal resistivity in the soil can be done using the power cables as the heat sources and the DTS fiber to measure temperature. By adjusting the soil thermal resistivity while comparing the measured temperature from the DTS fiber and a calculated temperature at the same location in the soil, the effective soil thermal resistivity can be determined.

In ampacity calculations, the earth thermal resistance is typically calculated from the following equation:

$$\overline{R_{Earth}} = \frac{\overline{\rho_{backfill}}}{2 \cdot \pi} \cdot \left[\ln\left(\frac{4L}{D_{Earth}} \cdot F_{Mutual} \right) \right] + \frac{\overline{\rho_{native}} - \overline{\rho_{backfill}}}{2 \cdot \pi} Gb$$

Using the thermal equivalent of Ohm's law, we know that:

$$\Delta T = \overline{R_{Earth}} \cdot W$$

The above equation says that heat, W, flowing through a thermal resistance, R_{Earth}, causes a temperature rise, ΔT , above the ambient earth temperature. Normally in an ampacity calculation, the allowable temperature rise and thermal resistance are known and the equivalent thermal circuit is solved for the heat output (or specifically the current).

However, if the cable shield or earth interface temperature is measured and the load is monitored (via SCADA or a CT), the earth thermal resistance can be found.

$$\frac{\Delta T}{W} = \overline{R_{Earth}}$$

Taking the above equation and substituting it into the equation for the earth thermal resistance, the effective soil thermal resistance can be determined by measuring the temperature rise above ambient and knowing the watts coming out of the cable, along with knowing the burial depth and diameter of the cable (or conduit):

$$\overline{\rho_{effective}} = \frac{\frac{\Delta T}{W} * 2\pi}{\ln\left(\frac{4L}{D_{Earth}} \right) + \ln(F_{Mutual})} \quad \left[\frac{C^\circ \text{-} m}{Watt} \right]$$

Alternatively, the temperature rise at a point in the soil can be determined by knowing the heat being generated in the soil and the mutual thermal resistance between the heat source and the measurement point (say a DTS fiber buried in a parallel conduit within the soil).

The heat source would be designated by specifying an X-Y location for the heat source and finding the total heat (I^2R and dielectric heating) from the source(s). With the heat output known for a given moment in time, the interference temperature rise at another location (the DTS fiber location) can be determined using the following equation:

$$\Delta T_{Interference} = W \cdot \overline{R_{Mutual}}$$

The mutual thermal resistance is based on the traditional Neher/McGrath calculation. The above application assumes that the heat source is infinitely long (like the cable itself) and in parallel.

When multiple cables are present, the mutual heating and interference temperature contributed by all of the cables to the DTS fiber location must be considered. Figure 3-5 illustrates using the method of images to determine the mutual thermal resistance between a DTS fiber location and a

power cable. The distance from the fiber to the image of one of the cables, d_{f1}', is divided by the actual distance between the fiber and one of the cables, d_{f1}, to develop a factor, F. The mutual thermal resistance is then calculated using the following equation where $\bar{\rho}$ is the thermal resistance of the soil. The heat output from each cable, W, includes contributions of both a.c. and dielectric losses.[5] This procedure is repeated for each cable or other heat-producing source near the fiber. The combined effects of all the interference temperature rise calculations are added to the ambient temperature and should closely match the measured DTS temperature.

$$\overline{R_{Mutual}} = \frac{\bar{\rho}}{2\pi} \cdot \ln\left(\frac{d_{f1}'}{d_{f1}}\right) = \frac{\bar{\rho}}{2\pi} \cdot \ln(F)$$

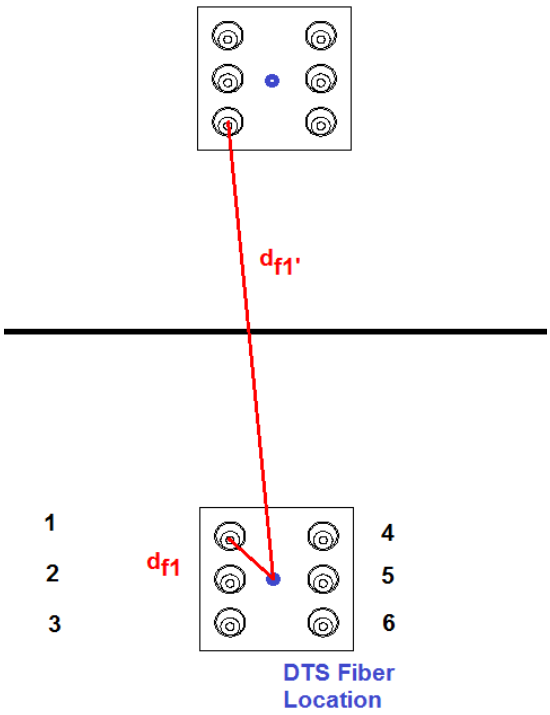


Figure 3-5
Calculation of mutual heating effect using the method of images

One of the challenges to this type of evaluation is that the recent loading on the cable system will likely be varying over a period of time. A procedure for considering this situation is to evaluate the average loading on the circuit over the last 1-2 weeks and determine what the steady-state temperature rise would be at the location of the DTS fiber. The average daily loss factor should be applied to the a.c. losses.

[5] If the load is variable, the a.c. losses should be multiplied by the daily loss factor.

3.3.1 Example Using UTWorkstation

This section provides a basic example of determining the effective soil thermal resistivity using EPRI's Underground Transmission Workstation (UTW). Figure 3-6shows a 230kV XLPE cable duct bank with two circuits. The vertical separation of the cables is 10in, and the horizontal circuit separation is 20in.

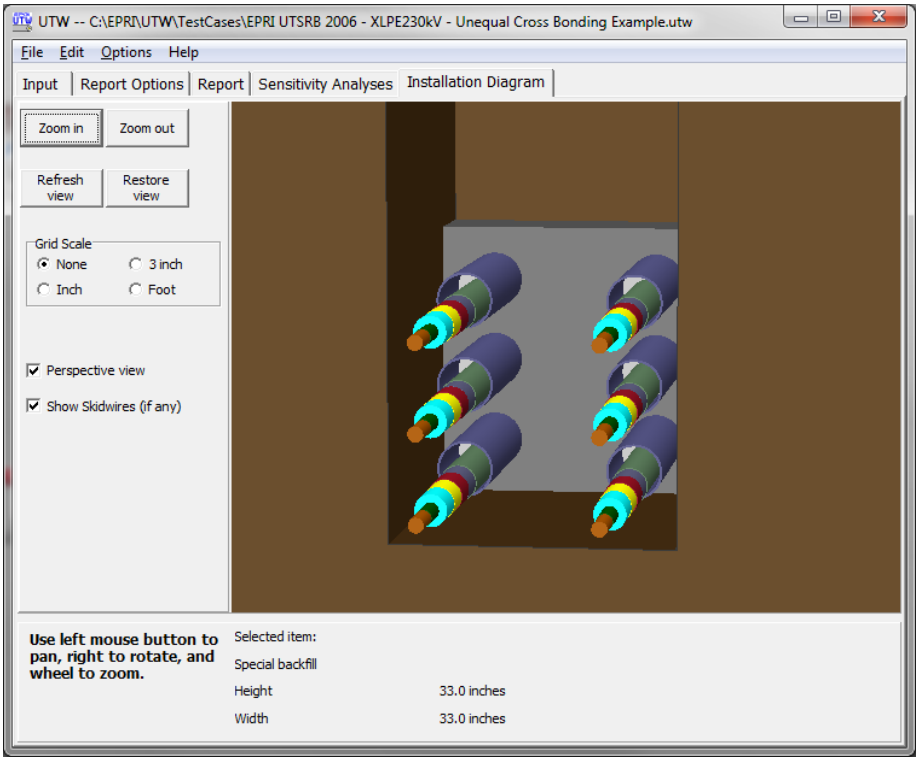


Figure 3-6
Example UTW cable configuration

For this example, a DTS fiber is assumed to be located at the center of the duct bank between the two middle cable phases (see Figure 3-7).

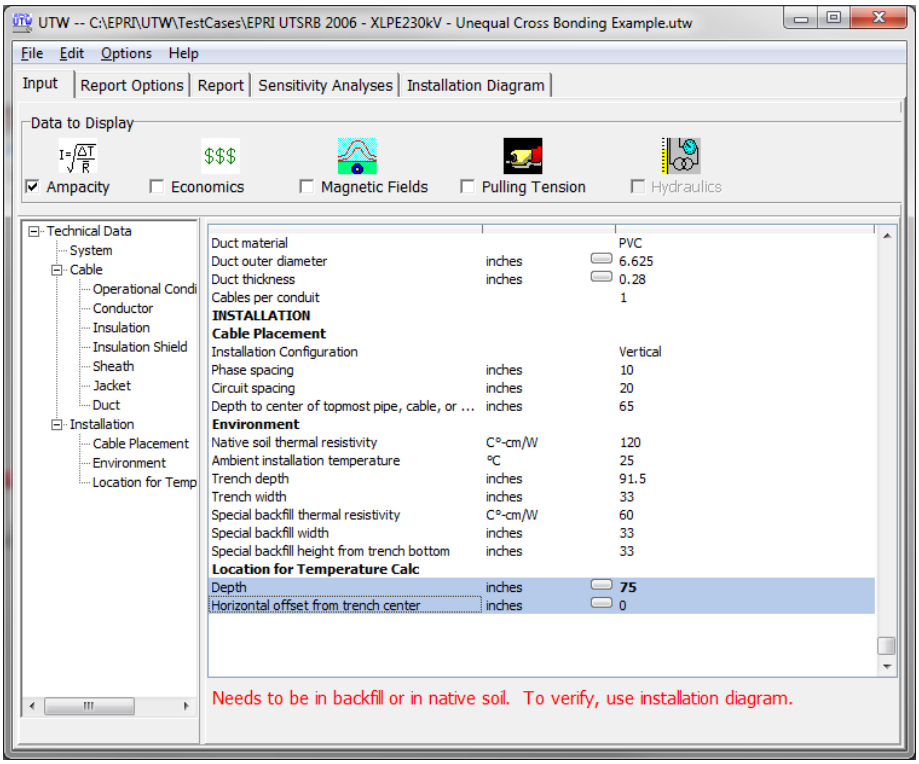


Figure 3-7
UTW input to specify location of DTS fiber (temperature calculation point)

The DTS-measured temperature was found to be 59.5°C when full rated load is on the cables for an extended period of time. Using the 120 C°-cm/Watt default thermal resistivity, UTW calculated a temperature of 63.2°C (see Figure 3-8).

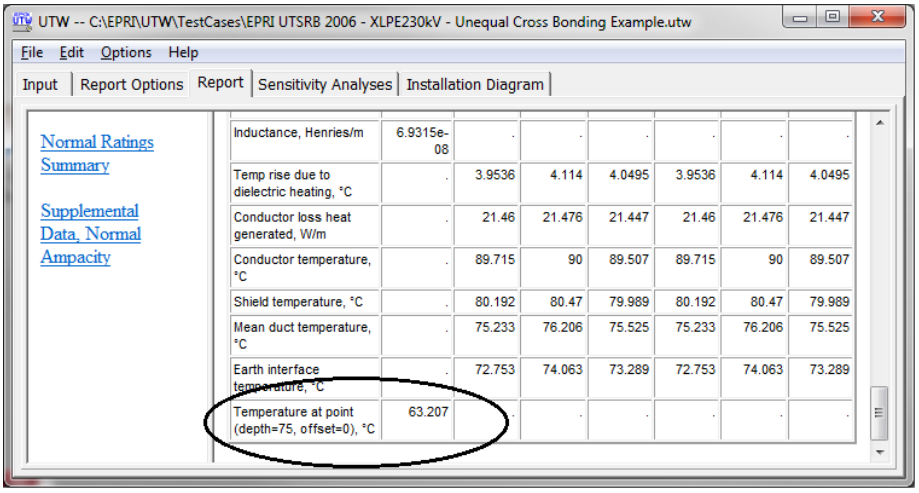


Figure 3-8
First iteration of calculated temperature

Since the calculated temperature is too high, a lower value of native soil thermal resistivity should be assumed. The value will be changed to 70 C°-cm/Watt. With this value entered, the calculated temperature is 57.5°C (too low, see Figure 3-9).

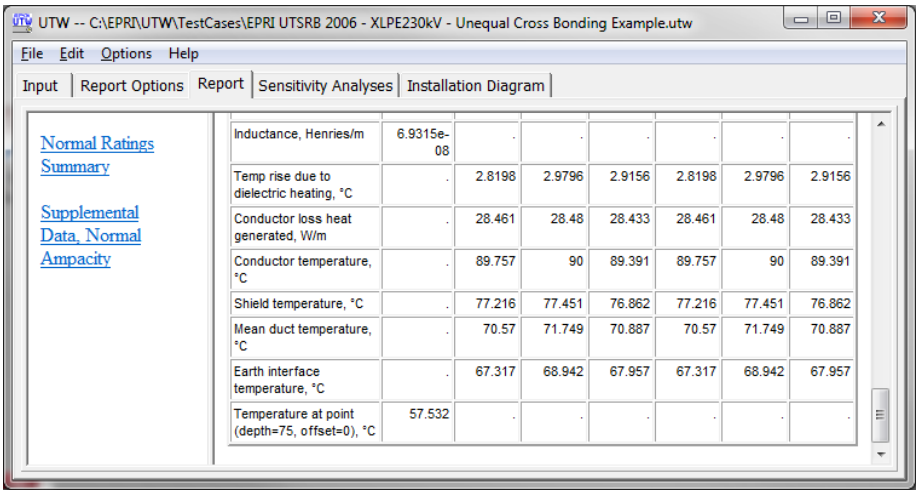


Figure 3-9
Second iteration of calculated temperature

By successively trying different soil thermal resistivity values, a value of 88 C°-cm/Watt is determined to be the best value. This soil thermal resistivity value is entered (Figure 3-10), and UTW performs the temperature calculations (Figure 3-11).

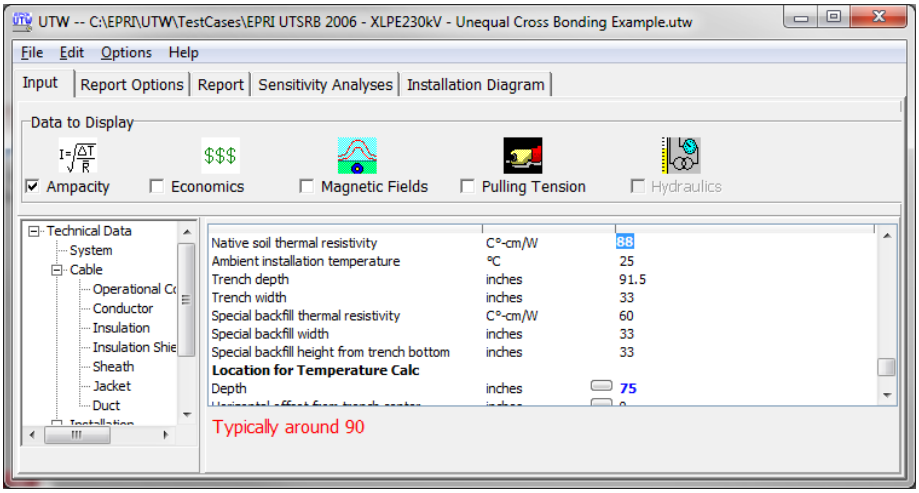


Figure 3-10
Setting the native soil thermal resistivity in UTW

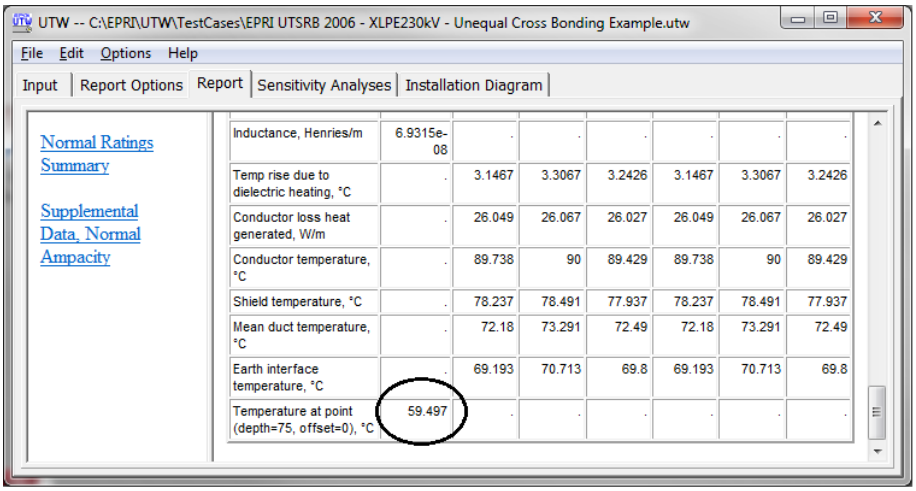


Figure 3-11
Calculated temperature at DTS fiber location matches measured value

Ampacity programs such as UTW also calculate the cable shield temperature and the earth interface temperature (other locations that are commonly outfitted with DTS fibers for temperature monitoring).

3.3.2 Interpreting DTS Temperatures with Low Circuit Loading

The example that was illustrated in the previous section assumed that the loading on the cable circuit was near full rated load. This resulted in an appreciable rise in temperature at the location where the DTS fiber was located.

Consider the cable configuration shown in Figure 3-6 and assume that a DTS fiber is integrated under the cable jacket. At full rated load (1090A), the conductor temperature is 90°C and the shield temperature would be 10-11C° less (~79.4°C); the total losses per cable would be approximately 8 Watts/ft with the shield temperature being 55C° greater than the ambient soil temperature (Table 3-2). With this high level of loading, a definitive comparison between measured shield temperature and the calculated shield temperature could be done to determine the soil thermal resistivity and verify other parameters used for ampacity.

However, if the loading on the circuit is only 25% of rated load (272A), the losses will be 1/16th of those at full rated load (neglecting that the dielectric losses will not change as long as the cables are energized at the same voltage) because the a.c. losses are a function of the current squared. In this condition, the shield temperature will be about 31.5°C (only about 6.5C° above ambient temperature), making it very difficult to accurately infer what the operating parameters at rated load will look like (Table 3-2). Small errors in measurements values would have a significant impact on extrapolating the conditions at full rated load.

Often, transmission cable systems are designed for N-1 (or N-1-1) loading scenarios where the normal rating is not important and the normal loading is often well below the normal rating. Under these circumstances, applying DTS measurements to obtain meaningful results is often difficult and care should be used when attempting to apply the results.

Table 3-2
Comparison Table of Cable Temperatures

Conductor Current (amperes) =	1090A		Losses:	8.0 Watts/ft		
Cable No.:	1	2	3	4	5	6
Conductor Temperature (°C):	90.0°C	87.8°C	89.1°C	87.8°C	90.0°C	89.1°C
Shield/Sheath Temperature (°C):	**79.4°C**	**77.3°C**	**78.5°C**	**77.3°C**	**79.4°C**	**78.5°C**
Cable Surface (°C):	78.5°C	76.4°C	77.7°C	76.4°C	78.5°C	77.7°C
Mean Cable-to-Conduit (°C):	75.0°C	72.8°C	74.1°C	72.8°C	75.0°C	74.1°C
Duct ID (°C):	71.4°C	69.2°C	70.5°C	69.2°C	71.4°C	70.5°C
Earth Interface (°C):	69.2°C	67.0°C	68.3°C	67.0°C	69.2°C	68.3°C
Ambient Earth (°C):	25.0°C	25.0°C	25.0°C	25.0°C	25.0°C	25.0°C
Conductor Current (amperes) =	273		Losses:	0.8 Watts/ft		
Cable No.:	1	2	3	4	5	6
Conductor Temperature (°C):	32.2°C	32.0°C	32.1°C	32.0°C	32.2°C	32.1°C
Shield/Sheath Temperature (°C):	**31.5°C**	**31.2°C**	**31.4°C**	**31.2°C**	**31.5°C**	**31.4°C**
Cable Surface (°C):	31.4°C	31.1°C	31.3°C	31.1°C	31.4°C	31.3°C
Mean Cable-to-Conduit (°C):	30.9°C	30.7°C	30.8°C	30.7°C	30.9°C	30.8°C
Duct ID (°C):	30.5°C	30.2°C	30.4°C	30.2°C	30.5°C	30.4°C
Earth Interface (°C):	30.2°C	30.0°C	30.1°C	30.0°C	30.2°C	30.1°C
Ambient Earth (°C):	25.0°C	25.0°C	25.0°C	25.0°C	25.0°C	25.0°C

3.4 Applications to Ampacity

3.4.1 Static Ratings/Off-Line Calculations

After finding the effective soil thermal resistivity as described above (or developing parameters that allow calculated temperatures to match the measured DTS temperatures), the resulting values can be used for input to off-line ampacity programs (i.e., UTWorkstation) or as input to real time rating software such as the Dynamic Thermal Circuit Rating (DTCR) system.

The procedures should be repeated periodically at different times of the year or under different loading conditions.

3.4.2 Real-Time Ratings

As was previously discussed, performing effective soil thermal resistivity calculations using off-line methods requires some interpretation of recent historical loading data. Real time rating systems have the ability to perform this interpretation and can do it continuously over time to trend resulting calculations.

EPRI's DTCR system performs this type of calculation. DTCR does not have automatic feedback of the calculated effective soil thermal resistivity but will report the value as an output parameter. DTCR can then be manually adjusted by an informed engineer to consider the effective soil thermal resistivity in the calculations.

4
DFOTS EQUIPMENT SUPPLIERS

4.0 DTS Equipment and Vendors

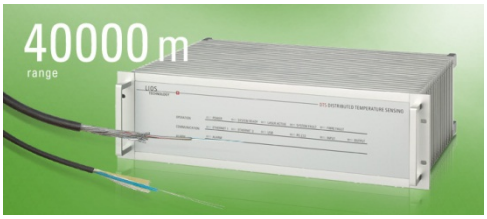
The following is a list of distributed temperature monitoring equipment suppliers that were identified at the time this report was prepared. A comparison table is provided that shows the major features of each type of equipment. This summary is not intended to provide an evaluation of the suitable nature of this equipment for a particular application. Information on the capabilities and characteristics were obtained from various web sites and product information collected during the course of this project.

- AP Sensing (Agilent)
  Contact: Greg McElyea
  Telephone:214-550-0677
  Email: greg.mcelyea@apsensing.com
  www.apsensing.com





- LIOS Technology
  Contact: Landry Molimbi
  1400 Campus Drive West
  Morganville, NJ 07751 USA
  Telephone: 732-970-8063
  E-mail: landry.molimbi@lios-tech.com
  http://www.lios-tech.com/US



- Sensornet
  Contact: Kuljit Singh
  Telephone: +44-20-8236-2555
  Email: Kuljit.Singh@sensornet.co.uk
  www.sensornet.co.uk



- Halliburton (SensorTran)
  Contact: Paul Nicholls
  Telephone: +44-1489-576648
  Email: Paul.Nicholls@halliburton.com
  www.sensortran.com



- Schlumberger (Sensa)
  Contact: Angel Larrea
  Telephone: 281-285-1825
  Email: JLarrea@slb.com
  www.sensa.org



- Sumitomo/J-Power Systems
  +81-3-5232-4714
  http://www.sumitomoelectricusa.com/products/fiber-optic-distributed-temperature-sensing-systems.html



- Qualitrol
  Telephone: 585-586-1515
  www.qualitrolcorp.com/Products/C_GUARD_Distributed_Temperature_Sensor_(DTS)



Table 4-1
Key Feature Comparison of DTS Equipment

Name	Maximum Range, km with min. 1m spatial resolution	Technology	Protocols	Quoted Accuracy	Operating Environment	Maximum Fiber Sensors
AP Sensing	12km	OTDR; single or double ended; multimode	SCPI, Modbus, TCP/IP	<1.5C° at 12km	-10°C to +60°C (rack); -25°C to +60°C (field unit)	Up to 24
LIOS Technology	40km	OFDR, multimode (<=40km); single mode	IEC60870-5, IEC61850, DNP3	<1.0C° at 20km <2.0C° at 40km	-10°C to +60°C	Up to 16
Sensornet	30km	OTDR, single or multimode	Modbus, OPC, WITSML	<1.0C° at 20km	+5°C to +40°C	Up to 16
Halliburton (SensorTran)	15km	OTDR, multimode	Modbus, TCP, OPC, DNP3, WITSML, Profibus, RS422, RS485, relays	<2.0C° at 15km	0°C to 40°C	Up to 16
Schlumberger (Sensa)	15km	OTDR, single or multimode	Modbus, OPC, relays	<1.0C° at 10km; <2.0C° at 15km	0°C to 40°C	Up to 12 single ended
Sumitomo (J-Power)	15km	OTDR	Not Specified	<1.0C° at 15km	Not specified	1 (16 for 6km unit)
Qualitrol	15km	OTDR, single or double ended, single or multimode	Modbus, DNP3, IEC61850	<1.0C° at 15km	Not specified	Up to 16

4.1 DTS Interpretation Software

- Tendeka FloQuest – Software provides a way of processing DTS output files to provide for adjustments, corrections and filtering of results.
- CymCAP/RTTR – A real-time rating package based on the offline cable rating program CymCAP.
- EPRI Dynamic Thermal Circuit Rating (DTCR) – System primarily provides real-time ratings for cables but can evaluate the effective soil thermal resistivity by comparing measured soil temperatures from DTS fibers to calculated values.

5
CONCLUSIONS AND RECOMMENDATIONS

5.0 Conclusions and Recommendations

- Distributed fiber optic temperature measurements on power cables is an effective way to determine their ultimate cable rating capabilities, verify as-built ampacity and design assumptions, and to monitor the cable system for hot spots.
- Successful application of DTS equipment to underground cable systems requires careful consideration of the many factors outlined in this report. Equipment capabilities must be carefully assessed relative to the particular cable circuits being monitored to be sure there is a good fit between the selected system and the particular application.
- Despite some of the DTS systems existence for more than 15 years, reliability data on these systems is not widely available. Informal discussions and observations of a few EPRI member utilities indicates that despite low failure rates, DTS equipment generally requires some level of service at least once every 5 years.

6
CONCLUSIONS AND RECOMMENDATIONS

The following references were used as background for preparing this report or have information that may be of interest as additional background reading:

1. *EPRI Increased Power Flow Guidebook*. EPRI, Palo Alto, CA: 2011. 1021877.
2. E.C. Bascom, III, et. al., "Taking Your Cable's Temperature", *Transactions of the T&D World Expo*, 7-9 May 2002, Indianapolis, Indiana.
3. *Ampacity Evaluation and Distributed Fiber Optic Testing on Pipe-Type Cables Under Bridgeport Harbor*. EPRI, Palo Alto, CA: 2002. 1007534.
4. *Novel Applications of Fiber Optic Sensor Technology for Diagnostics of Underground Power Cables*. EPRI, Palo Alto, CA: 2004. 1008712.
5. *Application of Fiber-Optic Temperature Monitoring to Solid Dielectric Cable: DFOTS Installation at Con Edison*. EPRI, Palo Alto, CA: 2000. 1000469.
6. *Condition and Power Transfer Assessment of CenterPoint Energy's Polk-Garrott Pipe-Type Cable Circuit*. EPRI, Palo Alto, CA: 2002. 1007539.
7. *Application of Fiber-Optic Distributed Temperature Sensing to Power Transmission Cables at BC Hydro*. EPRI, Palo Alto, CA: 2002. 1000443.
8. *Future Inspection and Monitoring of Underground Transmission Lines*. EPRI, Palo Alto, CA: 2009. 1020168.
9. P.B Oberson, et. al., "Optical Frequency Domain Reflectometry with a Narrow Linewidth Fiber Laser", *IEEE Photonics Technology Letters*, Vol. 12, No. 7, July 2000.
10. IEEE Guide for Temperature Monitoring of Cable Systems, 1718-2012.

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