Report to CIGRE WG B2.36 (Guide on Direct Real Time Rating Systems)
Stockholm, Sweden, May 20-21, 2010

Error Sources of Real-Time Ratings Based on Conductor Temperature Measurements

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1. Objectives

The primary objective of real-time rating is to provide to the operators information of the maximum current which can be applied on the conductor without violating the statutory or design clearance limits of the line. In principle, this can be accomplished either by:

a. Monitoring the tension or the sags of the line. This information ensures that the clearances are not violated. To determine the line ratings, the tension or sag information must be converted to the average temperature of the conductor in the relevant line section, representing the ruling span conditions between the dead-end structures. This process is called "line calibration' and is dealt with in a later document which discusses the errors inherent in sag/temperature calculations. When the average temperature of the line section is known together with ambient temperature and solar radiation, algorithms based on either CIGRE or IEEE Standards can be used to solve the convection cooling of the line, resulting in accurate real-time line ratings.

b. The other alternative is to measure the temperature of the conductor directly with sensors on the conductor. The temperature data, as well as the ambient temperature and solar radiation are then used to determine the line rating. The primary questions are then the required number of such sensors, their proper locations and their measurement errors. These are the subjects of the present report.

   While the knowledge of the average temperature of the conductor can be used to determine the line rating, there is no assurance that the computed rating ensures the primary objective, i.e. that of assured clearance, unless the line is properly calibrated. Thus, while direct temperature measurement, if conducted accurately, provides information leading to a rating that meets the thermal objective; it cannot by itself provide information about the sags or assure that satisfactory clearances of the spans of the line are maintained.

2. Thermal Balance

It has been long recognized that the relationships governing the thermal balance of the conductor include several variables which vary slowly and benignly over time and distance. These variables are ambient temperature, solar radiation (or their combined effect, solar temperature) as well as outgoing radiation losses [1]. On the other hand, the convection losses which depend on wind speed and direction vary rapidly both in time and spatially. These effects are extensively discussed in CIGRE TB 299 [2]. Because of this, no credibly accurate rating system has been developed based on weather measurements only. This is why CIGRE WG B2.36 classifies rating schemes based on weather measurements as "indirect real-time systems".

IEEE 738 and its extensive references show us that within the natural confines of a transmission corridor the conductor temperature varies substantially because of varying wind speed and direction. These variations are especially significant when wind speeds are low, i.e. during the most critical cooling conditions, and where the convection cooling is the least, i.e. in the most sheltered sections of the transmission line. References in IEEE 738 show that in typical transmission corridors the effective wind speeds are only a fraction of those of the typical open-terrain sites nearby, such as weather stations at airports.

One of the key objectives of the present report was to identify and classify such convection-based temperature variations along transmission lines and identify the reasons and magnitudes of such variations.

3. Test Site

The tests were conducted at and by Oak Ridge National Laboratories, on a test line of two full-scale 183 m spans, installed in a relatively narrow corridor sheltered by 15 m trees. See Figures 12 and 13. The two conductors of the span are designated “treeside” (closer to the edge of corridor) or “roadside”. As shown by the later data, the slight difference in sheltering causes the temperatures of the “treeside” to be slightly higher than those of the “roadside”. While narrow, the corridor does not differ significantly from 115 kV tree-sheltered compact line transmission corridors in the U.S. Because of this, it exhibits the same tendency as observed in actual transmission lines in that the wind directions tend to be determined by the transmission corridor, rather than the wind directions above the canopy of trees [3]. For the two key dates (January 4/5 2010) of the tests, wind roses showing the prevalent wind directions are presented in Figures 1 and 2.

The temperature of the conductors was monitored using thermocouples, installed close to the ends of each span, at the location of maximum sag and at the quarter-points of each span. At each site there were either two or four thermocouples at the surface; at some sites there were also thermocouples to monitor the core temperature. The surface temperatures of the thermocouples at each site were averaged to represent the temperature at each of these sites.

The conductor is heated with a 4 MW DC source. During a typical test run, the conductor current is controlled to result in a given average temperature (e.g. 100^o on January 4/5) by maintaining a constant DC resistance. As shown in Figures 3 and 4, the control system typically maintains the target average temperature within a standard deviation of about +/- 2^oC. Other instrumentation recorded line tension, sags, wind speed and direction at two different locations, ambient and solar temperatures during the test runs. Data was recorded at five minute intervals.

The conductor in the tests was ACSR 26/7 400 mm^2 “Drake”, one of the most ubiquitous conductors in the transmission systems of the world. While composed of a two-layer construction, and thus not exhibiting a large core/surface temperature gradient, (average 2.5^oC) it is well representative of typical transmission conductors. The conductor was prestressed for 24 hours. The peak tension recorded during the pre-stress period was 45 kN at -9^oC, i.e. 33% of rated strength.

4. Temperature Observations

Earlier observations in special HTLS conductor tests at the same site [4] had indicated that the temperature is highly variable both in time and spatially. It was also found that the conductor temperature was highest at the lowest elevations and that the elevation-effect was about 40-50% of the total variation, the rest being attributed to random variation. The recent tests were intended to clarify the dependence and distribution of temperatures, especially regarding more common ACSR conductor limiting temperatures around 100^oC, vs. 180^oC during the earlier HTLS conductor tests.

Raw data of the temperature observations of January 4/5 is shown in Figures 3-6. It is evident from the data that none of the individual temperature sensors represents the average temperature of the two test spans during the test runs. To further analyze the results, one can look at the average temperature values during the test runs, at each of the recorded locations during the 10/12-hour test runs. These are shown in Figures 7-8. Because the current of the test line is automatically adjusted to maintain a given average temperature of the conductor, the averages of temperatures at each site during the test run provide accurate means of studying the systematic error sources of local temperature readings compared to the objective of real time ratings based on average temperatures. There are two trends in these variations, namely the longitudinal variation and the variation depending on the elevation above the ground. These two effects can be separated by analysis of the two components. The third effect, also described below, is that of random temporal variation at each location.

4.1. Temperature Variation by Conductor Elevation above Ground

Wind speed increases with increasing elevation. This is a well-known fact, recognized by transmission line structural designers. While its effect on conductor temperature has been reported earlier [2],[4],[5], its effect on temperature monitoring is less well recognized.

Each of the ORNL spans has five sensor locations with multiple thermocouples. Two of them are at 7.6 m from the ends of the span. Two are at quarter-points, 45.8 m from ends and one at mid-span. At 100°C conductor temperature, the respective ground elevations during the January 4/5 tests were 10.6 m, 6.0 m, and 4.3 m. The data in Figures 7-8 shows that the temperature variation between the endpoints with maximum ground elevation and the span midpoints with minimum ground elevation varies between 15°C and 26°C, with an average of 20°C.

4.2. Longitudinal Temperature Variation

It is known that winds in sheltered transmission corridors tend to be predominantly directed along the transmission corridor [2]. This effect is self-evident even for any layman who has visited Manhattan or Chicago in wintertime, and learned how to preserve their umbrellas by pointing them in the right direction! While sheltering by trees is not as effective as that by buildings, it is more than sufficient to result in dominantly longitudinal flows. This has been observed in all prior studies made at the ORNL site. Thus, wind roses such as depicted in Figures 1 and 2 are quite typical for the ORNL site.

Separating the longitudinal component from average temperature variations in Figures 7-8, provides us the longitudinal temperature gradients of the spans and allows us to calculate the average temperatures of each of the spans during each of the tests. They are shown in Table 1 below:

Table 1. Average Temperature Difference between the Ends of the 363 m Test Site

	January 4	**January 5**
Treeside	28°C	29°C
Roadside	26°C	26°C

4.3. Random Variation

The remainder of the temperature variation consists of random variability, caused primarily by fluctuation of wind speed and direction. This can be separated from the total variation by mathematical analysis. The standard deviation of this variation, during the two days of tests is shown in Table 2 below:

Table 2. Standard Deviation of Random Variation During Tests

	January 4	January 5
Span 1 treeside	15.8°C	12.8°C
Span 2 treeside	14.2°C	12.1°C
Span 1 roadside	15.9°C	12.7°C
Span 2 roadside	12.9°C	11.1°C

Thus the random variability at any location is typically 12-15°C.

5. Heat Sink Effects of Temperature Monitors

Heat sink effects of sensors have been observed in various studies but explicit information of them is seldom reported. Some information from reports of large, 3-10 kg thermal sensors of 1990's indicated that the heat sink effect (i.e. the temperature reduction caused by mounting a 3-10 kg sensor on conductor) could be as much as 15-20% of the temperature rise of the conductor, even when sensors were designed to minimize the contact surface between the sensor and the conductor. The heat sink effects depend on two factors:

a. Temperature monitors are in thermal contact with the conductor. Because of their size, they increase the effective cooling surface which generally causes a negative heat sink effect (recorded temperature is less than that of undisturbed conductor). On the other hand, some studies have indicated that under parallel flow conditions, the monitors may have a <u>positive</u> heat sink effect, i.e. the reported temperature is higher than that of undisturbed conductor. This is caused when the sensor becomes an obstruction to the parallel wind flow, thus reducing the wind speed around the sensor's attachment area.

b. The mass of the sensor changes the thermal time constant. Thus, under varying wind and current conditions, the temperature change of the sensor lags that of the conductor without sensors.

These effects were studied at ORNL with two different sensor replicas applied to the line, depicted in Figure 9a and Figure 9b. One of the sensors is a replica of a commercially available light-weight sensor. The other was a replica of a relatively light-weight sensor, formed by an aluminum cylinder of 60 cm length and 4.4 cm diameter. The second sensor has a mass of 180% of equal conductor length and a cooling area of 160% of equal conductor unit length. The replicas were mounted near the end of spans 1 and 2, as is the most common practice for sensor mounting. The temperatures recorded by thermocouples in the sensor replicas were compared to thermocouples located at the conductor surface 1.5 m from the replicas. The difference denotes the sensor thermal sink effects. Data of the temperature measurements during April 2010 were used in the heat sink analysis.

The statistical variation of the heat sink effects during the test runs are depicted in Figures 10 and 11. Note that the variation of the heat sink effect indicates that it cannot be modeled as a constant temperature value or a percentage. This is evident considering thermal modeling relationships, as the heat sink effect is a function of wind speed and direction, as well as absolute temperature rise. Note, moreover, that the heat sink effect of a given sensor depends on the size and properties of the conductor upon which it is applied. Thus, a given sensor has a larger heat sink effect if applied on a smaller conductor.

The data in Figures 10 and 11 indicates that Sensor 1 had a heat sink effect of 38°C +/- 10°C. Sensor 2 had a heat sink effect of 11°C+/-5°C. The average temperature rise over the ambient at the surface thermocouples during the tests was 80°C. Thus the relative heat sink effects were 45% and 13%, respectively.

6. Conclusions

1. The ORNL tests show conclusively that even theoretically perfect sensors of conductor temperature (without heat sink effects) at discrete locations of a line have unacceptably large errors when applied to real-time rating purposes. The location-dependent (elevation and longitudinal distance) average error at the test site is +/- 20-30^{o}C when conductor temperature was 100^{o}C, and its application for real time rating would cause very severe systematic over- or underestimates in ratings.

2. Any sensor mounted on a conductor represents a heat sink and also a possible wind obstruction. Even the lightweight sensor replicas mounted on the test line were shown to indicate unacceptable temperature reductions. Typical commercial sensors may have even larger heat sink effects. The heat sink effects cannot be eliminated by modeling and would typically result in overestimates of real-time ratings.

3. Manufacturers of conductor temperature sensors should publish experimental data of the heat sink effects of their sensors.

4. Furthermore, because of communications, installation and durability reasons, it is a common practice to install temperature sensors near the ends of transmission spans. This practice results in underestimating the conductor temperature and overestimating the conductor ratings.

5. Even without heat sink effects, the large variability of the temperature along the ruling span indicates that adequate determination of the conductor's average temperature would require at least 5-8 sensors distributed along the ruling span.

References

1. Dale A. Douglass: Wind Speed for Line Ratings with Time, Sheltering and Instrumentation. IEEE PES Panel, Denver, CO, USA, June 2004.
2. CIGRE TB 299: Guide for Selection of Weather Parameters for Bare Overhead Conductor Ratings. CIGRE 2006.
3. Tapani Seppa: Wind Speed and Solar Radiation Data in Transmission Line Environments. IEEE SPM Panel, San Diego, CA, USA, July 1998.
4. Herve Deve: Weather Observation and Thermal Rating in a Short, High Temperature Test Line. IEEE-PES Panel, Denver, CO, USA, June 2004.
5. T.L. Jones, C.H. Chih, T.J. Whitaker: Conductor Temperature Dependency on Wind Direction and Weather Dynamics in Virginia. IEEE CP, January 1991.

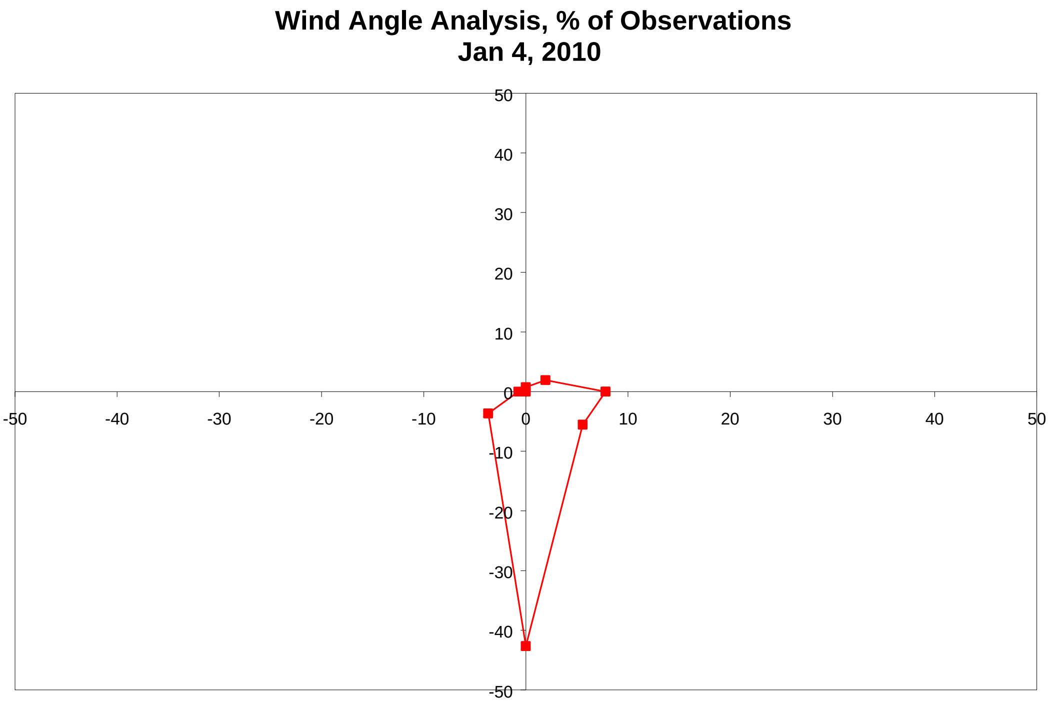


Figure 1

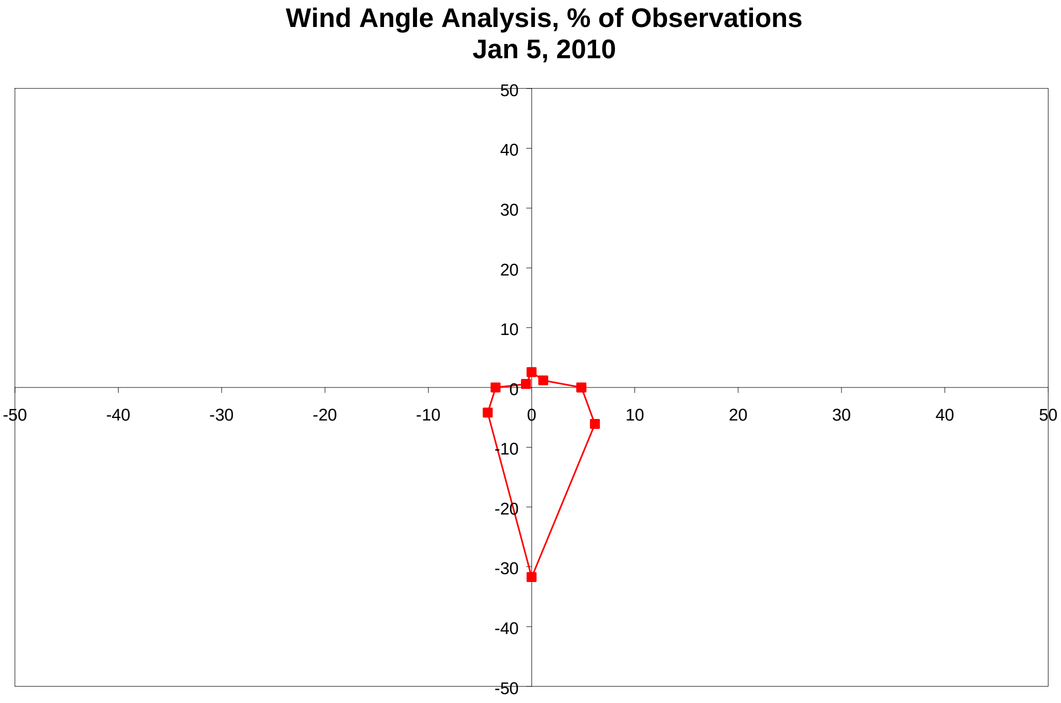


Figure 2

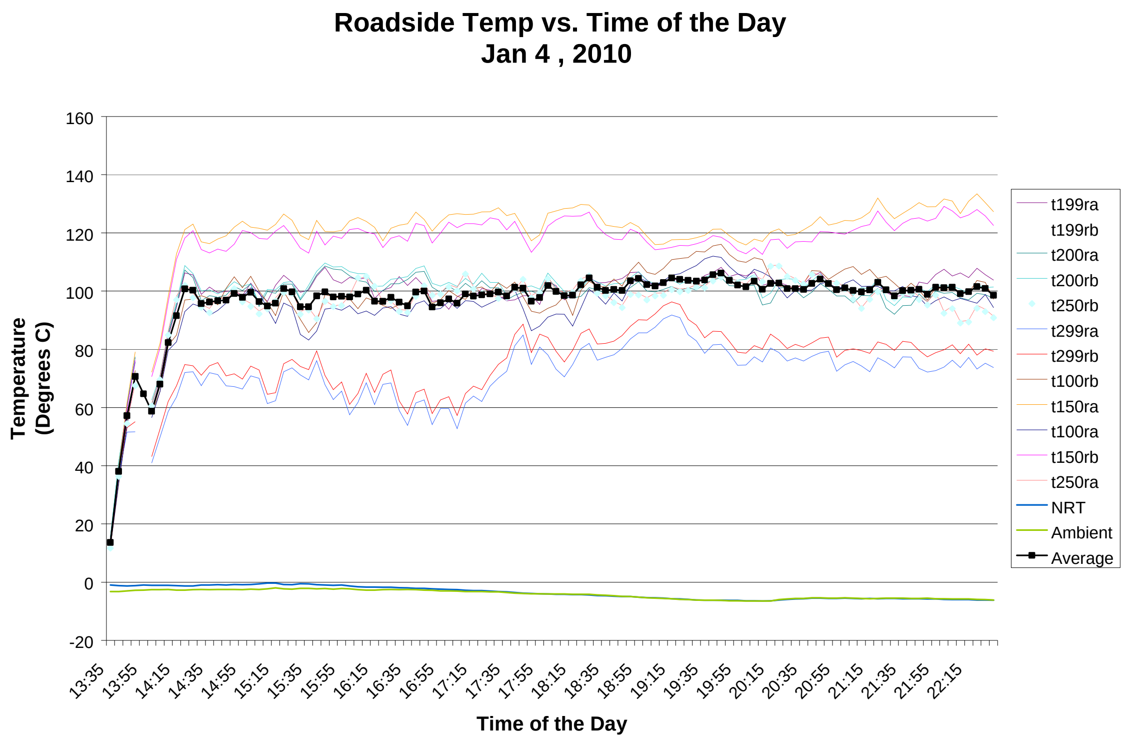


Figure 3

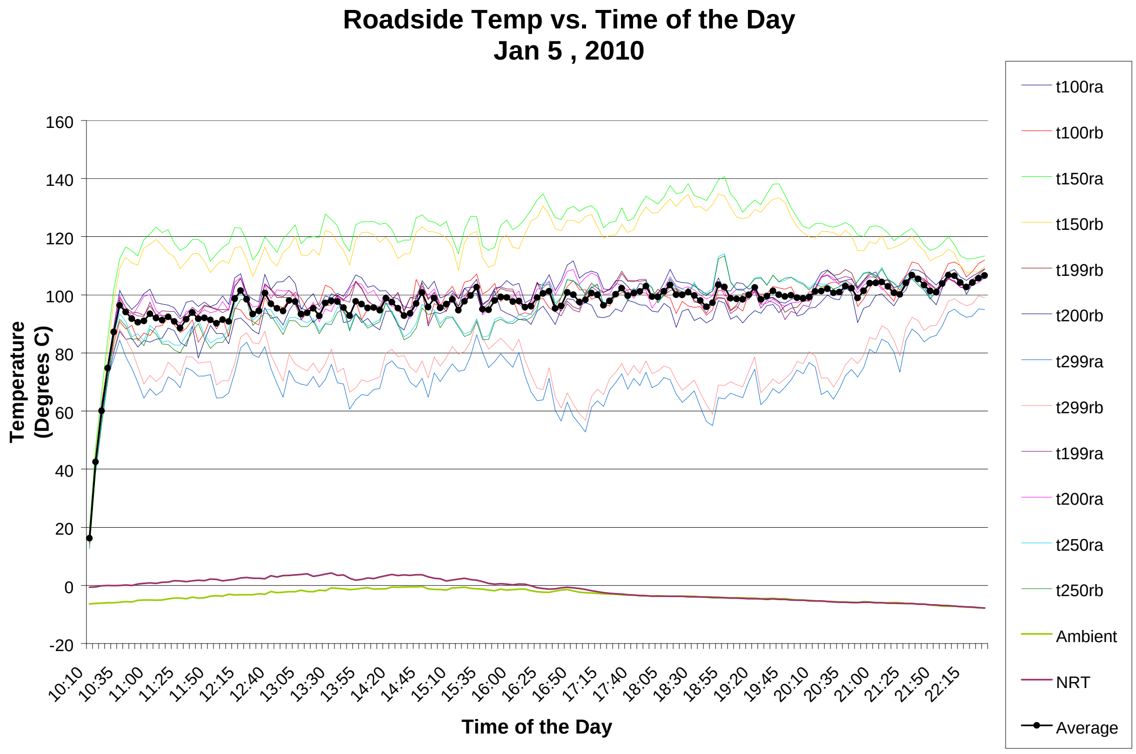


Figure 4

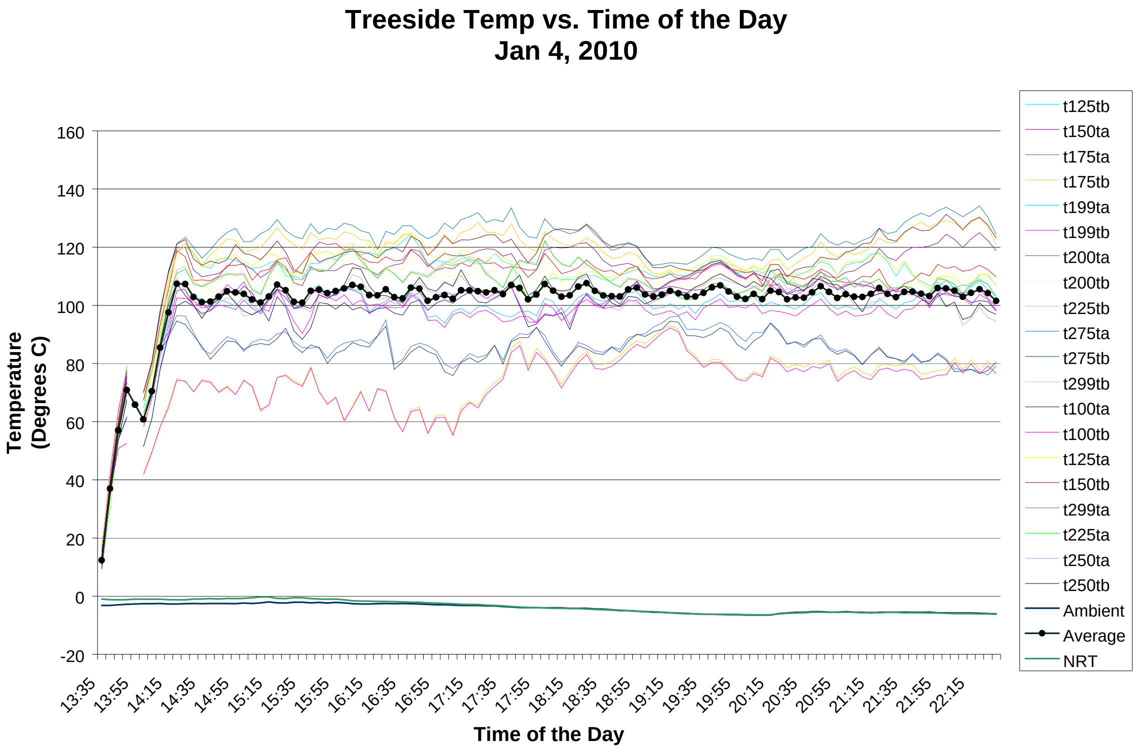


Figure 5

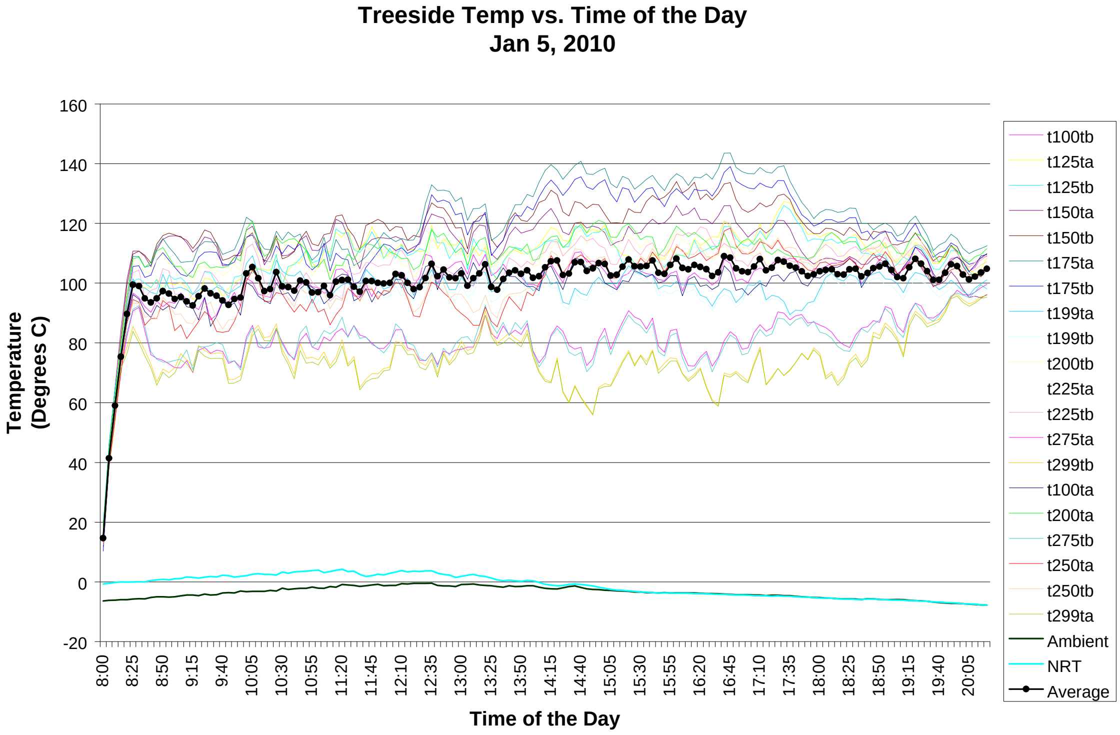


Figure 6

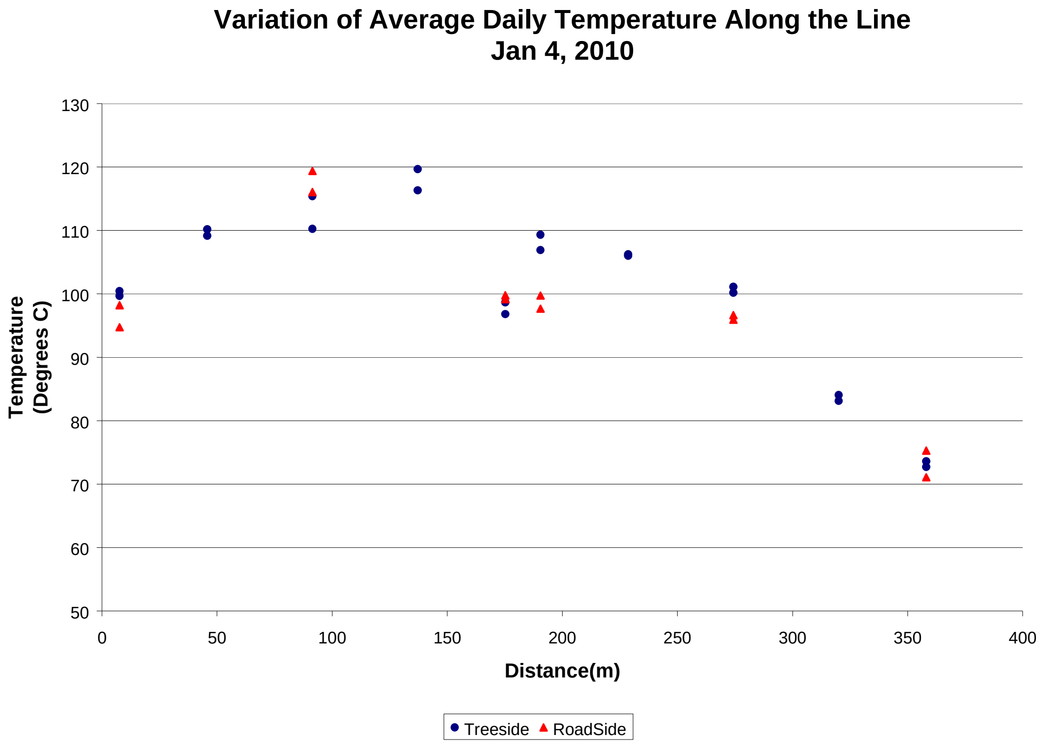


Figure 7

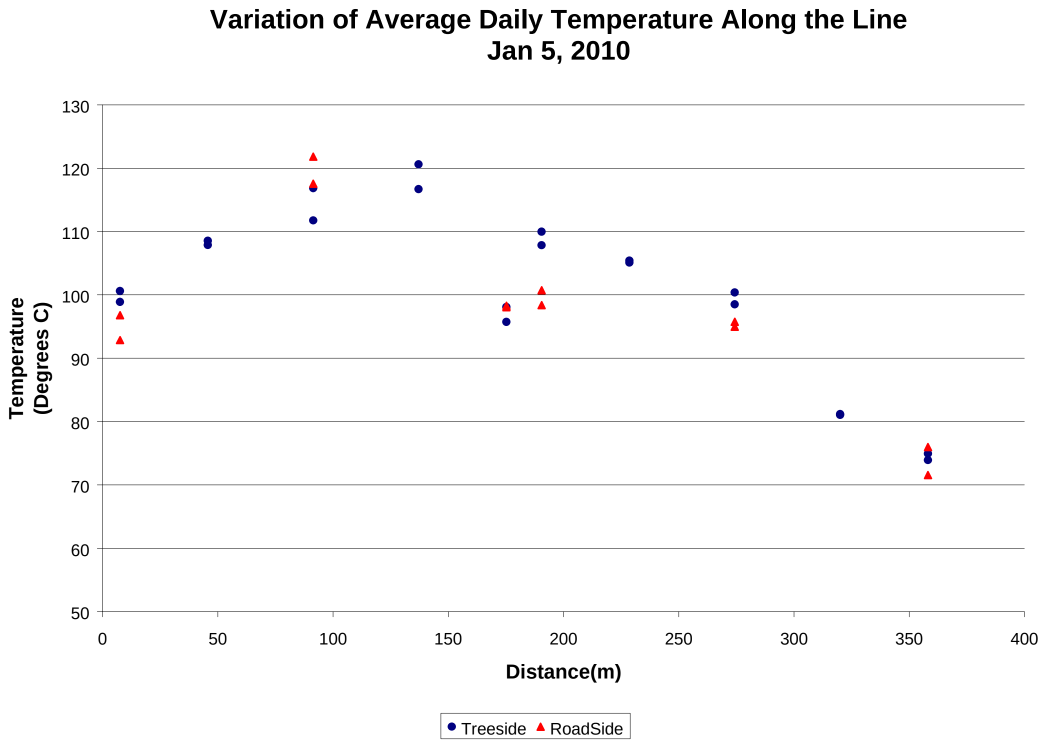


Figure 8

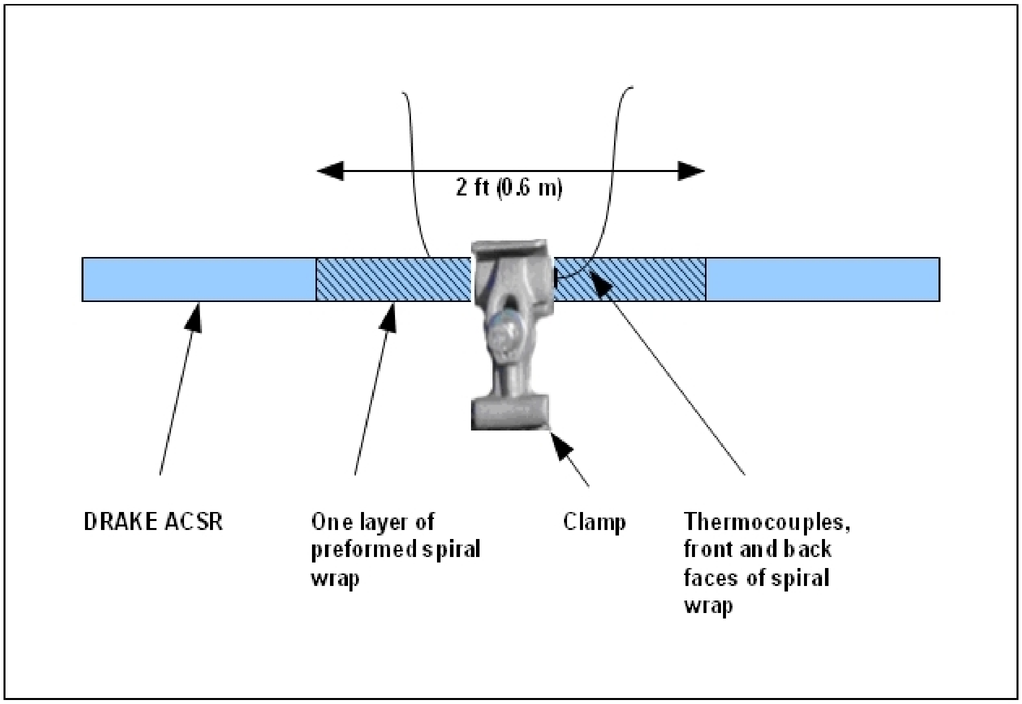


Figure 9a

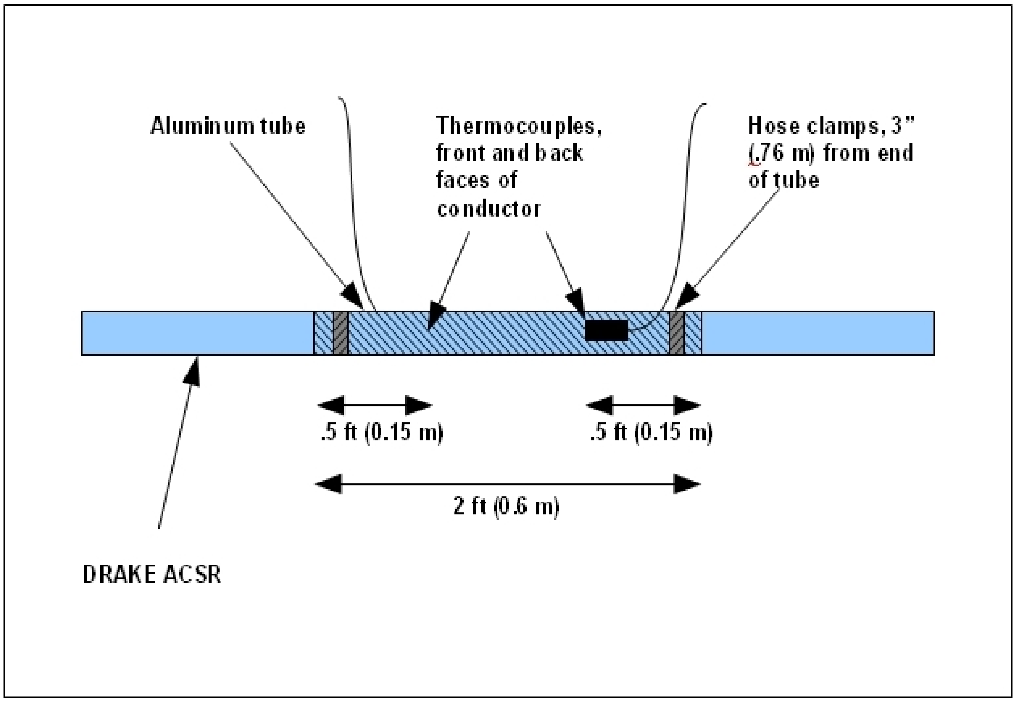


Figure 9b

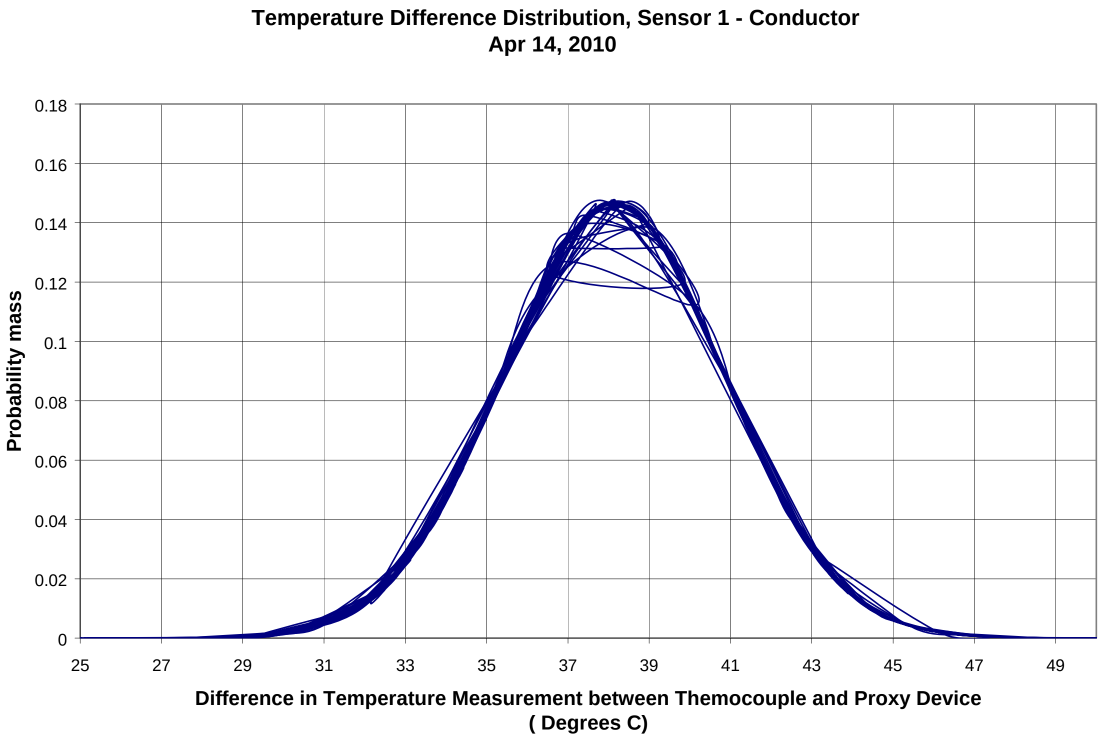


Figure 10

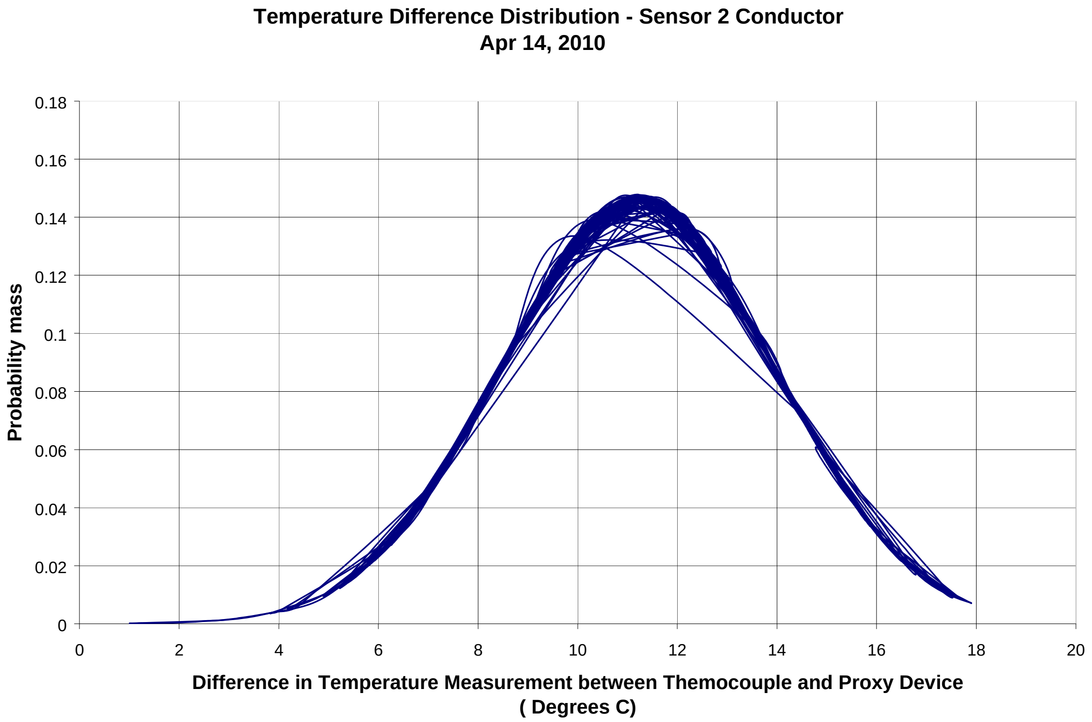


Figure 11

Layout of Transmission Test Line

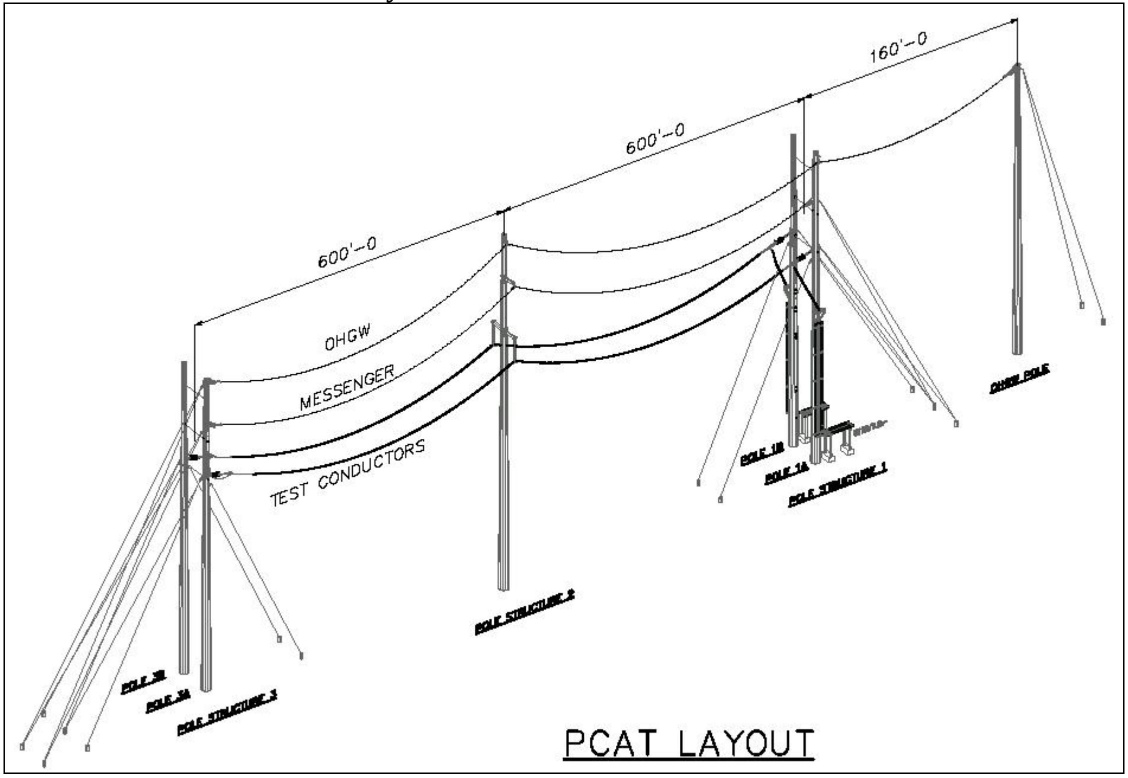
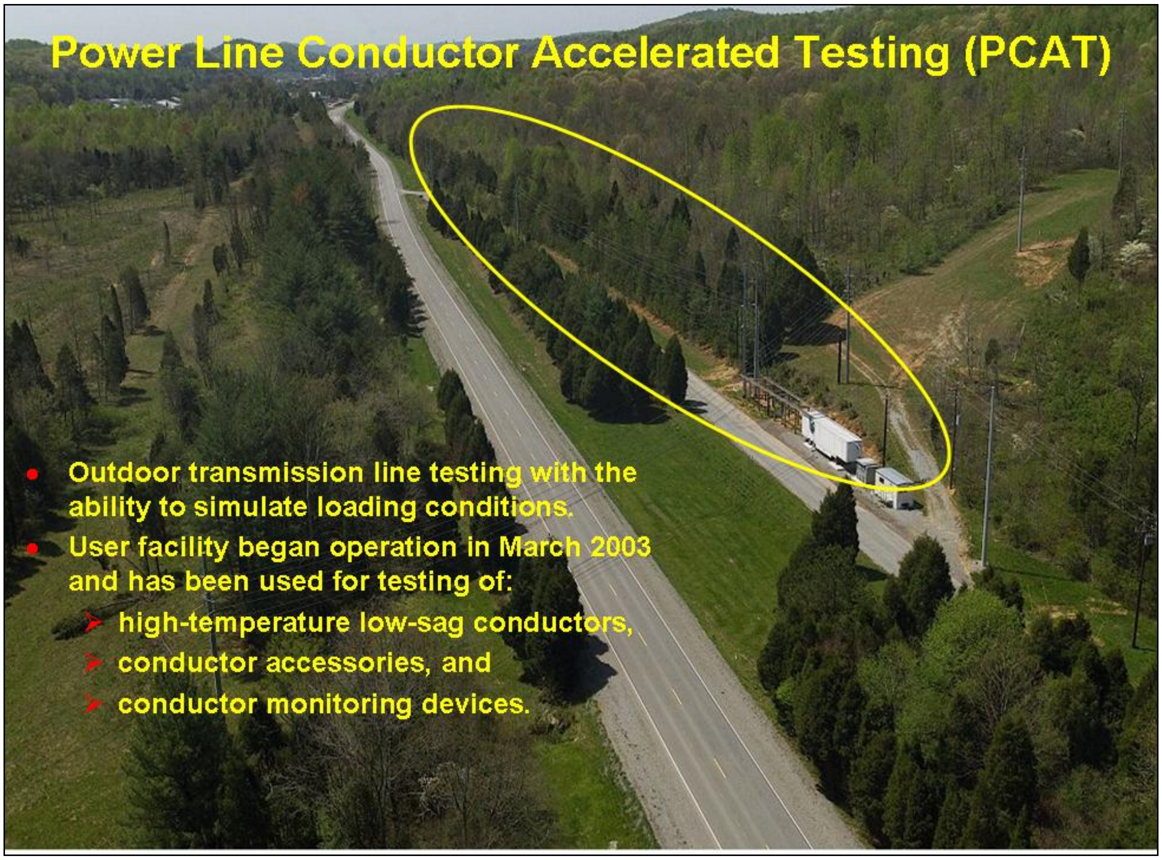


Figure 12

Photo of Test Site



Power Line Conductor Accelerated Testing (PCAT)

- Outdoor transmission line testing with the ability to simulate loading conditions.
- User facility began operation in March 2003 and has been used for testing of:
  - high-temperature low-sag conductors,
  - conductor accessories, and
  - conductor monitoring devices.

Figure 13