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Energy and Transportation Science Division

CRADA Final Report
For
CRADA Number CR-98-000535

Testing of the 3M Company ACCR Conductor

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Testing of the 3M Company Composite Conductor

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ABSTRACT

The 3M Company has developed a high-temperature low-sag conductor referred to as Aluminum-Conductor Composite-Reinforced or ACCR. The conductor uses an aluminum metal matrix material to replace the steel in conventional conductors so the core has a lower density and higher conductivity. The objective of this work is to accelerate the commercial acceptance by electric utilities of these new conductor designs by testing four representative conductor classes in controlled conditions.

Overhead transmission lines use bare aluminum conductor strands wrapped around a steel core strands to transmit electricity. The typical cable is referred to as aluminum-conductor steel-reinforced (ACSR). The outer strands are aluminum, chosen for its conductivity, low weight, and low cost. The center strand is of steel for the strength required to support the weight without stretching the aluminum due to its ductility. The power density of a transmission corridor has been directly increased by increasing the voltage level. Transmission voltages have increased from 115-kV to 765-kV over the past 80 years. In the United States, further increasing the voltage level is not feasible at this point in time, so in order to further increase the power density of a transmission corridor, conductor designs that increase the current carrying capability have been examined.

One of the key limiting factors in the design of a transmission line is the conductor sag which determines the clearance of the conductor above ground or underlying structures needed for electrical safety. Increasing the current carrying capability of a conductor increases the joule heating in the conductor which increases the conductor sag. A conductor designed for high-temperature and low-sag operation requires an engineered modification of the conductor materials.

To make an advanced cable, the 3M Company solution has been the development of a composite conductor consisting of Nextel ceramic fibers to replace the steel core and an aluminum-zirconium alloy to improve the outer strands. The result is a cable that can carry more current than steel-aluminum lines without sagging as much at higher temperatures.

A unique facility called the Powerline Conductor Accelerated Testing (PCAT) Facility was built at ORNL for testing overhead conductors. The PCAT has been uniquely designed for testing overhead bare transmission line conductors at high currents and temperatures after they have been installed and tensioned to the manufacturer's specifications. The ability to operate a transmission line conductor in this manner does not exist elsewhere in the United States.

Four classes of ACCR cable designed by 3M have been successfully test at ORNL – small, medium, large and small/compact. Based on these and other manufacturer tests, the 3M Company has successfully introduced the ACCR into the commercial market and has completed over twenty installations for utility companies.

1. STATEMENT OF OBJECTIVES

One of the critical aspects of increased power flow for utilities is the significant change in operating conditions, and it is imperative to demonstrate to the utilities that composite conductor and accessories can operate safely at high-temperature and under thermal cycling. It is also important to demonstrate that the sag-temperature-current characteristics are predictable even after repeated thermal cycles.

Installation and operation of the composite conductor in field trials is typically not well suited for controlled testing of elevated temperature cycling because the load is not easily controlled or predicted. The factors leading to high-temperature excursions include: line current loading, contingency conditions, wind, and solar exposure. Depending on these conditions, it can take a year or more for the conductor to experience a single emergency load.

High-temperature exposure and thermal cycling of the conductor and accessories under mechanical load can be more easily achieved on a test line that operates at low voltage with a controlled current. Such a test line would be able to simulate thirty years of emergency conditions in three months. ORNL has built a low-voltage test line to evaluate the high-temperature operation of ACCR.

To move ahead and introduce the new technology, ACCR will be tested across the following critical conductor classes or sizes which are typically used for U.S. grid installations:

- Small size, round wire - 477 kcmil "Hawk"
- Small size compact - 675 kcmil "Hawk/TW"
- Medium size, round wire - 795 kcmil "Drake"
- Large size, round wire - 1272 kcmil “Pheasant”

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2. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

ORNL has built a unique transmission test facility to support the nation's need to address electricity transmission reliability and security issues. While the demand for power in the U. S. is expected to rise 25% in the next 10 years, the current transmission capacity relative to growth has declined. The problems and solutions to this trend are highlighted in the *"Report of the President's National Energy Policy Development Study"* [1] and the *"National Transmission Grid Study"* [2]. The specific recommendation in the Grid Study pertaining to the transmission test facility is as follows:

> *"DOE will develop national transmission-technology testing facilities that encourage partnering with industry to demonstrate advanced technologies in controlled environments. Working with TVA, DOE will create an industry cost-shared transmission line testing center at DOE 's Oak Ridge National Laboratory."*

The transmission test facility has been uniquely designed for testing overhead bare transmission line conductors at high currents and temperatures after they have been installed and tensioned to manufacturer's specifications. The ability to operate a transmission line conductor in this manner does not exist elsewhere in the United States.

This CRADA benefits the DOE mission by the potential increase in electric transmission line capacity without the construction of new lines. The line upgrading made possible by this work will improve energy efficiency of the electric grid without the adverse environmental impact of major line reconstruction.

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3. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

The project goal is to accelerate the commercial acceptance of the high-temperature low-sag conductors. 3M Company has developed a new class of overhead conductors based upon a fundamental change in materials. These high-performance composite conductors, also referred to as Aluminum Conductor Composite Reinforced (ACCR), rely on a core of aluminum composite wires surrounded by temperature resistant aluminum-zirconium wires. They represent a major change in overhead conductors since conventional aluminum-steel reinforced conductors (ACSR) were introduced in the early 20th century.

The development of metal composite wire for overhead transmission lines offers two major benefits: increased power flow and increased efficiency. On an everyday basis, ACCR operates with lower electrical losses due to the conductivity of the core material and lack of ferromagnetic losses. When required, ACCR can provide transmission capacities double that of existing systems. The low thermal expansion of the composite core keeps line sag within design limits when power flow increases. ACCR can be used as a replacement conductor, with quick installation and minimal disturbances to neighborhoods and the environment. No modifications on existing transmission towers or foundations are needed.

The project object has been to verify the aluminum composite conductor and accessory performance by providing engineering performance data, based upon field testing including testing at rated conductor temperatures. ORNL entered into a cooperative research and development agreement with the 3M Company to test their conductor.

3.1 Test Facility Design and Construction

The ORNL test line incorporates multiple instrumentation systems including (1) a CAT-1 system for measuring conductor tension and weather (ambient & solar temperatures and wind conditions), (2) multiple thermocouples mounted at various locations on the conductor and accessories and connected to A/D (analog/digital) modules and fiber optic modems to monitor temperature profiles, (3) measurement of the conductor voltage and current during the testing to calculate its resistance as a function of operating temperature, (4) a laser range finder for measuring conductor clearance and calculating sag during the tests and (5) a data acquisition system (computer, software and fiber optic network) for gathering, archiving, analyzing and displaying the data measurements and controlling the dc power supply.

The facility was designed and constructed in 2002 and 2003 with the assistance of TVA as shown in Figure 1. The test line is 1200 feet in length with 600 ft. spans and the test conductor is installed as two circuits (a total of four 600 ft. spans). At the power supply end (Structure #1), the two circuits are connected to the positive and negative terminals of a dc power supply. At the far end (Structure #3), the circuits are connected together. The result is a 2400 ft. loop of conductor to the dc power supply as the resistive load. The dc power supply is rated at 5000 Adc and 400 Vdc.

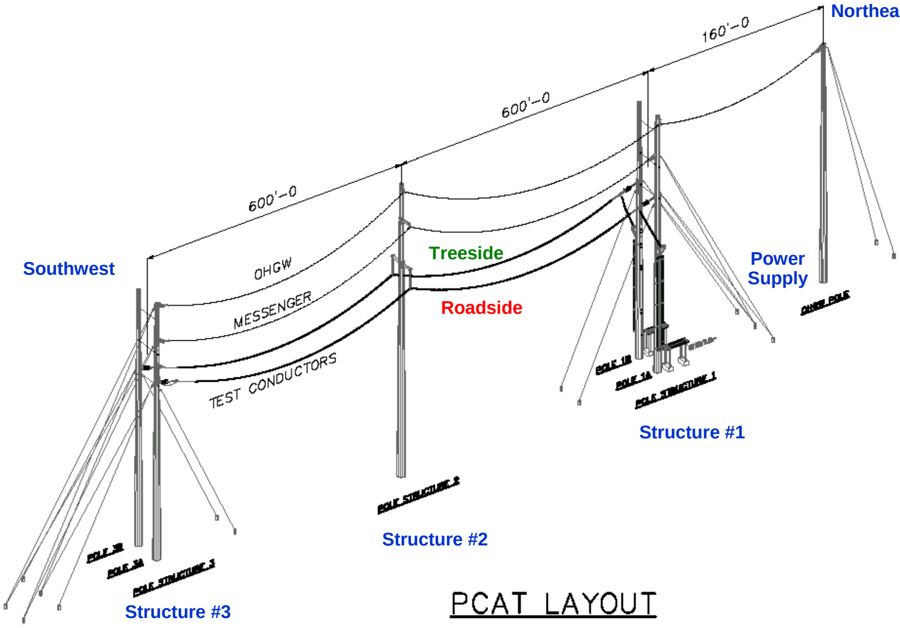

Figure 1. Layout of PCAT Facility

The following conductor tests can be performed: knee-point curve measurement, emissivity measurement, constant current and temperature tests, current ramp tests, and thermal/mechanical cycling tests. A typical testing period is 4 to 10 months in duration.

During the testing, the following parameters are measured on a one-minute basis.

- Conductor temperature using Type T thermocouples placed on the surface of the conductor every 150 ft. along the 1200 ft. test length.
- Accessory temperatures using Type T thermocouples placed on the surface of two dead ends, two splices, one suspension and one jumper
- Conductor tension using a load cell.
- Conductor clearance at one mid-span using a laser range finder.
- Conductor current and conductor voltage drop as measured by the dc power supply.
- Weather conditions – ambient temperature, wind speed and wind direction, solar radiation.

A 2.25 MW dc power supply is used to apply current to the test conductor. The power supply is rated 0 to 5000 Adc and 0 to 400 Vdc. A manual limit can be set to prevent the power supply from operating above a specified current. A conductor temperature limit can be set and based upon the real-time measured conductor temperature; the power supply can be turned off.

3.2 ACCR Testing Summary

Four sizes of ACCR were tested from August 2002 to August 2009. A summary of these tests are given in this section and for each test a report can be found in Appendix A.

3.2.1 ACCR 477 Kcmil Test

The ACCR 477 conductor was installed successfully on the ORNL- PCAT line using commercial hardware and normal installation procedures. The conductor and accessories were thermally cycled from ambient to over 200ºC for several hundred hours, using DC power supply and as high current as 1200 amps. The measured sag matched the SAG-10 (recognized as the industry standard software for calculating sag and tension prediction). Data analysis shows that the measured conductor current agrees well with the IEEE thermal rating model predicted values. After de-installation the conductor and accessories were tested for residual strength and degradation. Residual strength exceeded 100% RBS (rated breaking strength) and neither conductor nor accessories showed any signs of damage. Conductor resistance after cycling is equivalent to that of conductor not exposed to thermal cycling.

3.2.2 ACCR 795 Kcmil Test

The ACCR 795 conductor was successfully installed and tested at ORNL. It was thermally cycled from ambient to over 200°C for several hundred hours, using a DC power supply. Measured temperature difference between conductor core and its surface was as low as 5°C and as high as 20°C degrees and depended on both wind speed and core temperatures at and above 200°C. Wind speeds above 0 fps (foot per second) produced larger temperature gradient from surface to core.

Data analysis shows that the measured conductor current agrees well with the IEEE thermal rating model [3] predicted values. The conductor is rated at 1653 A current for continuous operation at 210°C and at 1778 A emergency current at 240°C. The CIGRE model agrees with the IEEE 738 model.

Conductor tension was stable during and after thermal cycling. Measured line tension versus temperature agrees well with values computed using the strain summation method, STESS.

Both PLP (Preformed Line Products) and AFL (Alcoa Fujikura Limited) accessories ran cool, below 120°C at conductor's temperature exceeding 200°C. The conductor and accessories were exposed for up to 1000 hours at high temperature and show no visual damage. Conductor was de-installed in early 2006 and shipped to NEETRAC for inspection and mechanical testing (residual strength).

3.2.3 ACCR 1272 Kcmil Test

The ACCR 1272 conductor was successfully installed in Aug. 2004 and tested at ORNL. It was thermally cycled from ambient to greater than 200ºC for several hundred hours, using DC power supply. Measured temperature difference between conductor core and its surface was only several degrees at cycling temperatures in excess of 200°C. The wind speed appears to have a strong effect on cooling of the conductor.

Data analysis shows that the measured conductor current agrees well with the IEEE thermal rating model predicted values. The conductor is rated at 2229 amps for continuous operation at 210ºC and 2402 amps emergency operation at 240ºC. The CIGRE model agrees well with the IEEE 738 model within 0.8%.

The conductor sag was stable during and after thermal cycling. Measured line tension agrees well with values computed using the strain summation method. Both PLP and AFL accessories ran cool, 120ºC and show no visual damage.

The conductor was de- installed in June 2005, and sent to NEETRAC (National Electric Energy Testing Research and Applications Center) for testing and evaluation.

3.2.4 ACCR 675-TW Kcmil Test

The ACCR 675 TW conductor was installed successfully on the ORNL PCAT Line using commercial hardware and normal installation procedures. The conductor and accessories were thermally cycled from ambient to greater than 200ºC for several hundred hours, using a DC power supply and currents as high as 1500 amps. The measured sag matched the SAG-10 prediction. Data analysis shows that the measured conductor current agrees well with the IEEE thermal rating model predicted values. After-de installation the conductor and accessories were tested for residual strength and degradation. Residual strength exceeded 100% RBS and neither conductor nor accessories showed any signs of damage. Conductor resistance after cycling is equivalent to that of a conductor not exposed to thermal cycling.

3.3 Variability of Conductor Temperature

A large number of prior reports have indicated substantial temperature variability within a single span in test lines and significant variation of temperature between point measurements in adjacent spans due to varying wind conditions. More anecdotal evidence, e.g. in the discussion records of the Proceedings of the IEEE Panel on Dynamic Line Ratings on July 20-21, 1982, indicate that, at high temperature, longitudinal temperature variation of 10-25ºC had been observed in a single span. Accurate documentation of such variation is generally not available.

It is also generally recognized that the tension and sags of a line section between two dead-ends should be a function of the average temperature of the conductor. Observations have generally shown a good correlation between measured temperatures and sags, but high quality data for comparisons has typically not been available.

Because the high temperature conductor tests at the ORNL PCAT facility are extremely well instrumented, these tests can provide answers to the above questions. The complete report is in Appendix B and shows a much larger longitudinal temperature variation than previously documented.

3.4 Project Presentations

During the project, presentations were made at the U.S. Department of Energy's Transmission Reliability Program Peer Reviews and these presentations are in Appendix C. Open to the public, these meetings reviewed the research and development projects designed to help modernize the nation's electric grid. Energy sector stakeholders from outside the program attended the meetings to learn first-hand about the latest developments and integration activities. During the Peer Review, a panel of selected electricity industry experts performed a formal evaluation of projects, provided technical feedback and recommendations to ensure that the DOE continues to support projects that meet industry needs.

4. COMMERCIALIZATION POSSIBILITIES

The 3M Company has successfully implemented their commercialization plan for ACCR. The success, to date, is shown by the twenty-two utility customer installations of ACCR listed in Table 1. ACCR has been installed to meet challenges in a variety of locations, environments, and ampacity requirements.

3M ACCR Installations		**Application**	**kV**	**Conductor Size**	
				(kcmil)	(mm^2)
TATA Power	Mumbai, India	Load growth Dense population	110	300	150
Xcel Energy	Minneapolis, Minnesota	Installation validation	115	477	238
Hawaiian Electric Company	Oahu, Hawaii	Corrosive environment	46	477	238
Western Area Power Administration	Fargo, North Dakota	Heavy ice and wind loads	230	795	418
Bonneville Power Administration	Washington State	High temperature operation	115	675-TW	322-TW
Western Area Power Administration	Phoenix, Arizona	Installation validation	230	1272	642
Salt River Project	Phoenix, Arizona	High current operation	69	795	418
Pacific Gas & Electric	Santa Clara, California	High temperature operation	115	477	238
Xcel Energy	Minneapolis, Minnesota	Environmentally sensitive area River crossing	115	795	418
Arizona Public Service	Phoenix, Arizona	Dense population Underbuilds	230	1272	642
Western Area Power Administration	Arizona/California Border	High growth	230	795	418
Shanghai Electric	Shanghai, China	Cost and time savings	115	795	418
Platte River Power Authority	Fort Collins, Colorado	Increased reliability	230	954	490
Aha Macav Power Services	Needles, California	Increased reliability	69	300	150
Allegheny Power	West Virginia	Underbuilt facilities Cost and time savings	138	1033	525
British Columbia Transmission Company (BC Hydro)	British Columbia	River Crossing	230	788	400
Alabama Power	Birmingham, Alabama	Underbuilt facilities Load growth	230	680	346
Silicon Valley Power	City of Santa Clara, CA	Environmental and aesthetics Reliability	60	715	365
Chongqing	Chongqing, China	Load growth Time savings	220	680	346

3M ACCR Installations		Application	kV	Conductor Size	
				(kcmil)	(mm^2)
Companhia de Transmissao de Energia Eletrica Paulista	Sao Paulo, Brazil	Cost, time and environmental impact savings	138	300	150
Alabama Power	Birmingham, Alabama	Cost and time savings	230	1033	525
CPFL Piratininga	Jundiai, Brasil	Load growth Cost and time savings Social impacts	88	336	171

Table 1: List of 3M ACCR Installations

TATA Power Company

TATA Power is installing 125 miles (200 kilometers) of 300 kcmil 3M ACCR on two lines near Mumbai, Borivali-Malad and Salsette-Saki. The lines were upgraded a few years ago from a single to a bundled ACSR, but they could not keep pace with the rapid demand growth in the area. In addition, residences had sprung up directly under the lines, and TATA did not want to disturb them, but did want to improve clearances over them.

Xcel Energy

In 2001 Xcel Energy installed 477-kcmil ACCR in its 115 kV system in Minneapolis to feed power from a generation plant to the network. It replaced a conventional ACSR conductor to increase the ampacity while keeping the same clearance and tower loads.

Hawaiian Electric Company

Hawaiian Electric Company (HECO) installed a similar 477-kcmil 3M ACCR on a 46 kV line located on the North Shore of Oahu for the evaluation of ACCR corrosion resistance. In particular, the installation tests the corrosion resistance of the conductor on their 46 kV network while also increasing the ampacity along the existing right-of-way by approximately 72%.

Western Area Power Administration (Western)

Western is one of four power marketing administrations within the U.S. Department of Energy, and serves nearly 700 wholesale power customers in a 1.3 million-square-mile area, including some 300 municipalities, as well as public utilities and utility districts, energy cooperatives, power marketers, irrigation districts, Native American tribal communities and government agencies.

In 2002 795-kcmil 3M ACCR was installed by Western on the Fargo-Jamestown 230 kV line near Fargo, North Dakota. The climatic conditions there exposed the cable to high winds, extreme cold, ice loading and conditions conducive to aeolian vibration. ACCR was installed on a 1-mile stretch of the circuit. The first two winters after the line was energized were mild. However, in the winter of 2005/2006, ice built up on the conductor, doubling the span’s mechanical loads. Despite the ice loading, there have been no problems since the line was installed. The line data follows the predictions made by models for sag, tension, and rating.

Bonneville Power Administration (BPA)

In June of 2004 BPA installed ACCR 675T13-TW on a 115 kV line in Pascal, Washington as a replacement for an existing Chuker 1780 kcmil (976 mm2) ACSR bottom phase. The purpose of the installation was to test the operation of the compact trap-wire ACCR at elevated temperatures. 3M provided its 675T13-TW conductor to BPA for installation at their Pasco site as a replacement for an existing Chuker 1780-kcmil (976 mmm2) ACSR bottom phase. The conductor was installed in June

2004, energized in August 2004, and has run continuously since then. Despite running at currents as high as 1,100 A, conductor temperatures did not exceed 80°C (computed). The mechanical load versus NRS (net radiation sensor) temperature data at low current level matches the predicted values and has essentially been unchanged over time.

Western Area Power Administration (Western)

In January 2004 Western installed 1272-kcmil 3M ACCR at its Liberty-Parker location in Phoenix, Arizona. The conductor was installed as an evaluation/validation cable for the installation of cable constructions with three layers of aluminum. The measured conductor tension and sag agree with predictive models. The line has been loaded to around 25% of its electrical rating since June 2004.

Salt River Project (SRP)

3M ACCR has been installed in several locations in proximity to generating stations in order to test the conductor under high current loads where it will see high ambient temperatures. Conductors for these tests are sized so that they will operate at their maximum electrical design loads. SRP installed 795 ACCR on a 69 kV line at the expansion of their Santan generation plant in Gilbert, Arizona, in March of 2004. The 795 ACCR line delivers output of the Santan Expansion Project Unit 5b (combined cycle natural gas fired generator) to the 69 kV switchyard. The location is ideal to test 3M ACCR because it undergoes significant temperature swings and high summer peak demand (high conductor temperature) in desert conditions where ambient temperatures are very high.

Pacific Gas & Electric (PG&E)

PG&E in Southern California installed 3M ACCR on line segments near a substation in Santa Clara.

Xcel Energy

3M ACCR received its first commercial application when Minneapolis-based Xcel Energy installed it on a ten-mile (sixteen-kilometer) transmission line in the Minneapolis-St. Paul region. Xcel Energy is using the conductor to increase the capacity of a transmission line that extends from Shakopee to Burnsville. The upgrade is part of a US$100 million expansion project at the utility's Blue Lake peaking plant in Shakopee, which is needed to ensure a reliable supply of power to Xcel Energy's customers in the Upper Midwest during periods of peak electricity demand. The line crosses an interstate and two major highways at multiple points, as well as traversing several residential and industrial areas.

Arizona Public Service (APS)

APS installed 3M ACCR to increase capacity on a key overhead transmission line serving Phoenix, a growing metropolitan area. The new conductor eliminated the need for the utility to site, acquire right-of-way, and construct a new power line route in a congested downtown business area.

3M ACCR was installed on a six-mile, 230 kV power line extending from a local area power plant to APS' downtown substation. The installation provides increased capacity to service the fast-growing metropolitan area that experiences extreme summer heat. In this application, 3M's ACCR 1272-kcmil conductor was used to upgrade a line that already had been upgraded once with ACSS.

The utility selected ACCR as a result of a twelve-month evaluation of various high temperature, low sag conductors. 3M's ability to supply a complete package, including conductor hardware and installation support, was instrumental in the utility's selection of ACCR.

The Western Area Power Administration (Western)

Western, which delivers about 40 billion kilowatt-hours of hydroelectric power annually in fifteen western and central states in the U.S., chose 3M ACCR to replace a key conventional power line in western Arizona.

3M ACCR is installed on a twenty-mile stretch of the Topock-Davis 230 kV line, which parallels the Colorado River along Arizona's western border with California. The area of service includes fast-growing communities such as Lake Havasu City and Bullhead City in Arizona; Laughlin, Nevada; and Needles, California.

Shanghai Electric Power Company, Ltd

On October 14, 2007, Shanghai Electric became the first utility in Asia to install and energize 3M ACCR. Shanghai Electric, a publicly owned utility whose major shareholders are China Power Investment Corp. and East China Power Development Company, serves the Shanghai metropolitan area with more than 2,800 megawatts of generating capacity. Shanghai is the largest city in the People's Republic of China, and the eighth largest metropolis in the world. Shanghai Electric deployed 3M ACCR to shorten construction time and save costs while increasing capacity on a key 10-mile line serving the growing demand in the city of Shanghai.

Platte River Power Authority

To ensure adequate transmission capacity during summer peak demand hours, Platte River Power Authority installed the 3M ACCR as a replacement conductor on a key three-mile segment of a line that links Fort Collins and Loveland, extending from the Timberline Substation southward along the Union Pacific railroad right-of-way to the Harmony Substation.

Platte River Power Authority generates reliable, low-cost and environmentally responsible electricity for its owner communities of Estes Park, Fort Collins, Longmont and Loveland, Colorado, for delivery to their utility customers. Its facilities are located along the Front Range and northwestern Colorado in addition to near Medicine Bow, Wyoming. Installation is scheduled for Fall 2007.

Aha Macav Power Services

Aha Macav Power Services, a utility owned and operated by the Fort Mojave Tribe in the Southwest, is the first Native American utility to deploy 3M ACCR.

Under an agreement with the Western Area Power Administration (Western), Aha Macav installed a new four-mile 3M ACCR line linking a new substation in Arizona to a switchyard in Needles, CA, a city on the western bank of the Colorado River.

The new line substantially boosts power capacity and reliability for Needles and the surrounding area, which have been plagued by frequent electricity outages in recent years, often during periods of extreme high temperature. The Fort Mojave Tribe, whose reservation encompasses portions of eastern California, southern Nevada and western Arizona, is one of only a handful of tribes served by its own utility. Installation of the 3M ACCR was installed in March 2008.

Allegheny Power

Allegheny Power, a division of Allegheny Energy Inc., installed 3M ACCR to upgrade a 138 kV line linking the Bedington and Nipetown substations along Interstate-81 in West Virginia. The 1.7-mile upgrade boosted transmission capacity on a line some 50 miles northwest of Washington, D.C. The 138 kV line shares structures with three other lines for most of its length, including two under-built 12 kV lines, has a flow of 2,200 amps and is expected to peak at a temperature of 200°C. The line is built on self supporting steel poles with drilled pier concrete foundations.

3M ACCR gave Allegheny the ability to leave the under-built 12 kV circuits in service during construction and to avoid structure replacement. It also sags neatly with an adjacent 954 ACSR conductor on the same structure.

British Columbia Transmission Company

BCTC, the operator of the transmission system for the British Columbia province, installed 3M ACCR on two segments of the Vancouver Island Transmission Reinforcement (VITR) Project to minimize the disruption to the ecology of diverse and sensitive waterways. Larger towers to accommodate larger conductors or double bundling would require bringing heavy equipment into remote areas by barge; installing new foundations and towers; digging out the existing footings and then transporting the aggregate. Moreover, one of the segments goes through part of a provincial park where preserving the sightline was important. Using 3M ACCR, the transmission utility was able to meet these goals.

In addition, they were able to install the conductor through unusually long spans, avoiding adding towers to the line. One segment, the Sansum Crossing, included a 5,800 foot (1,770 m) single span. The second segment, the Montague Crossing, was a 6,000 foot (1,830 m) multi-span installation.

Alabama Power

Alabama Power Company, a subsidiary of Southern Company, will install 3M ACCR to upgrade a 1.7 mile line at their Miller Steam Plant, in Jefferson County, Alabama, approximately 25 miles northwest of Birmingham.

Alabama Power's upgrade, utilizing 3M ACCR 1033 kcmil 54/19 Curlew, will boost transmission capacity on a line that goes through and loops around the Miller Steam Plant. The upgrade is part of Alabama Power’s ongoing, multibillion-dollar environmental initiative, designed to reduce emissions from the company's power plants while continuing to meet the growing demand for power. The new 230 kV line, is rated to carry up to 2,000 amps and is expected to peak at a temperature of 200°C.

The existing line crosses below three 500KV line and above one 230KV line and is supported on five existing lattice steel structures. The 3M conductor provides the required capacity, while utilizing the existing structures and maintaining or improving the existing clearances to ground and other obstacles. As a result, significant savings were achieved in both time and cost by eliminating the need for the design, supply and construction of new towers.

Silicon Valley Power

SVP, the municipal utility of the City of Santa Clara, California, is located in the heart of the Silicon Valley area, where reliability is paramount for serving high-tech industries. Equally important are using existing structures and minimizing the disruption to both residential and business neighborhoods. This second installation of 3M ACCR will also be on an existing 60 kV line, from Keifer Receiving Station to Norman Avenue Junction, as well as two new sections from Norman Avenue to the new Palm Substation and back. The project also has to accommodate a 12 kV line running under the installation and a 115 kV line crossing above the installation in 2 locations, as well as multiple railroad and highway crossings. 3M ACCR’s strength to weight ratio and durable hardened aluminum will give them the needed reliability and additional capacity using only the existing structures.

Chongqing Electric Power Corporation

Chongqing Electric needed extra capacity to meet anticipated heavy power demand for the summer Olympics in Beijing and did not have time to construct new towers. Using existing towers, Chongqing Electric installed a two-circuit line of approximately 3.4 miles (5.5 kM), linking the Shuinian and Shuangshan substations. Chongqing is in a subtropical region with high humidity and frequently extreme summer heat, and 3M ACCR was chosen in part because of its proven reliability in difficult climates.

This installation will serve more than a half million residents within two districts in Chongqing City, an ancient city with a population of approximately four million located on the Yangtze River in southwest China, within Sichuan Province.

Companhia de Transmissao de Energia Eletrica Paulista

Companhia de Transmissao de Energia Eletrica Paulista (CTEEP) installed 300 kcmil 3M ACCR to upgrade a 138 kV transmission line crossing an environmentally sensitive river bed. CTEEP, which is principally owned by Grupo Empresarial ISA (ISA Group), one of South America's largest electricity and telecommunications providers, supplies almost all of the electricity consumed in the State of Sao Paulo and 30 percent of the electrical power consumed nationwide. The line boosts capacity for power transmission for the Jupiá Electrical System. The line crosses the nearly mile-wide Parana River and is subject to strong winds and extremely high temperatures. “3M ACCR was determined to be the most cost-effective, proven solution available,” says CTEEP engineering manager Caetano Cezario Neto. The installation was completed in just 6 days.

Alabama Power

Southern Company subsidiary, Alabama Power, installed 3M ACCR to replace a key 10-mile (16-kilometer) line in northeastern Alabama. The line was upgraded to meet contingency requirements resulting from the addition of generation to serve summer peak loads. 3M ACCR was chosen for this project to avoid replacing approximately half the transmission structures and installing eight additional structures, significantly reducing construction time and allowing the line to be taken out of service for this project without impacting grid reliability. Alabama Power Company supplies electricity to 1.3 million homes, businesses and industrial facilities.

CPFL Piratininga

CPFL, part of CPFL Energy Group, used 3M ACCR to expand transmission capacity in Várzea Paulista and Jundiaí (SP), Brazil. Because part of the existing line was located in an urban corridor with houses on both sides, installing new towers was deemed too risky, as the conductor ran over buildings and access to the line for foundation and structural work was difficult. Installing 3M ACCR provided the needed upgrade capacity without the need to construct new towers, accelerating and simplifying installation. CPFL Piratininga also chose 3M ACCR for its reliability.

5. CONCLUSIONS

A unique facility has been constructed at ORNL for testing of overhead conductors in controlled conditions. Conductors can be operated to simulate the range of current loading found on the electric utility system. The objective of the testing program for the 3M Company was is to accelerate the commercial acceptance by electric utilities of these new conductor designs.

Four classes of the conductors developed by the 3M Company have been tested. The conductors represent the range of conductor sizes that are in common use in the United States. A variety of tests were completed on each conductor including: knee-point curve measurement, emissivity measurement, constant current and constant temperature tests, current ramp tests, and thermal/mechanical cycling tests. The test reports for each conductor are in Appendix A.

Based upon the tests completed at ORNL and others by the 3M Company, the ACCR cable has achieved commercial success based on over twenty installations worldwide.

During the testing, conductor temperature variability within a single span of the test line and a variation of conductor temperature between point measurements in adjacent spans was noted and reported (Appendix C) to a CIGRE committee.

6. REFERENCES

1. National Energy Policy, .Report of the National Energy Policy Development Group, ISBN 0-16-050814-2, U.S. Government Printing Office, Washington, D.C., May 2001.
2. National Transmission Grid Study, U.S. Department of Energy, Washington, D.C., May 2002.
3. IEEE Std 738-1993, IEEE Standard for Calculation of Bare Overhead Conductor Temperature and Ampacity Under Steady-State Conditions

Appendix A.1

ACCR 477 Kcmil Test Report

Composite Conductor Field Trial Summary Report: ORNL ACCR 477 Kcmil

Installation Date	July 25, 2002
Field trial Location	Oak Ridge, Tennessee, USA

Line Characteristics

Organization	Oak Ridge National Laboratory
Point of Contact	John Stovall, ORNL
Installation Date:	July 25, 2002
Conductor Installed	ACCR 477
Length of line:	1,200 feet (365.7 meters)- 4 spans
Conductor diameter	0.858 inch, (21.8 mm)
Voltage	400 VDC
Ruling span length	600 feet, (183 meters)
Structure Type	Steel Poles
Instrumentation:	(1) Load cell (2) Current, voltage (3) Weather station (4) Sag (5) Thermocouples in conductor and accessories

Hardware

Suspension Hardware	Preformed Line Product, THERMOLIGN^{R} Suspensions TLS-0101-SE
Termination hardware	PLP THERMOLIGN^{R} Dead End TLDE-0104 Alcoa Compression dead end B9085-A PLP THERMOLIGN^{R} Splice TLSP-0104 Alcoa compression splice B9095-A Alcoa terminal connector B9102-A
Dampers	Alcoa Stockbridge dampers 1704-7
Insulator type	Polymer

Results and Measurements

Full range of temperature tests from 30^{o}F – 412^{o}F (0^{o}C – 240^{o}C) with currents ranging from 0 to 1,400 amps

- Conductor temperature (surface and core)
- Sag temperature from 0^{o}C – 240^{o}C
- Accessory temperature profile during thermal cycling
- Conductor and accessory strength after thermal cycling
- Measured vs predicted thermal rating

Acknowledgement:

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Table of Contents

Abstract:

Under DOE funding Agreement No. DE-FC02-02CH11111, ORNL jointly with The Tennessee Valley Group, TVA, successfully installed the ACCR 477 conductor on a high temperature test line at ORNL in July 2002. The test line consists of two 600 foot spans; two on the road side and two on the tree side between a steel suspension pole and two guyed, dual steel pole dead-end poles. The test conductor forms a loop connected to a DC power supply located at one end of the line, therefore a total of 2400 feet of conductor was tested.

The conductor was installed with commercial hardware developed for ACCR conductors. The line was fully instrumented with (1) thermocouples in the conductor and accessories, (2) a CAT-1 system to measure tension and (3) a full weather station.

Oak Ridge National Laboratory subjected the line to severe thermal cycling and extended high temperature load using 400 V DC and about 1200 amps depending on weather conditions. The conductor was thermally cycled from May 2003 to October 2003 between ambient and over 200^0 C for 200 hours. The conductor experienced over 100 cycles to elevated temperature. During the course of the cycling, conductor tension and temperature were monitored. The measured conductor tension - temperature response agreed with predictive models.

Predicted conductor current, using IEEE thermal rating ampacity method, agrees well with measured values. Conductor's emissivity of 0.347 was measured using IR method and used in the IEEE conductor- rating model.

Conductor and accessories were taken down from the line after thermal cycling and tested. The results showed that mechanical and electrical properties of the conductor and accessories were unchanged.

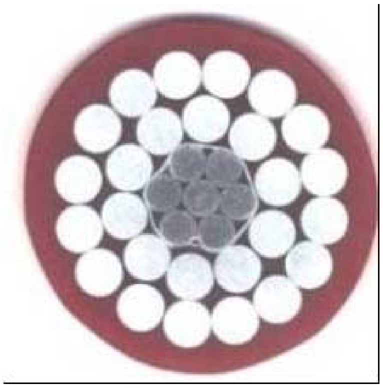
1- Background

Reliable high temperature performance is one of the key requirements for implementing new high temperature-low sag conductors. It is imperative to demonstrate in the field that the conductor and accessories can operate as predicted at high-temperature, under thermal cycling and without degradation. It is also important to demonstrate that the sag-temperature-current characteristics can be predicted after repeated thermal cycles. High-temperature exposure and thermal cycling of the conductor and accessories can be achieved on a test line that operates at low voltage with a controlled current. Such a test line is able to simulate lifetime field conditions in three months by applying dozens of emergency cycles where the conductor temperature exceeds the normal operating temperature of 210^{o}C, *($410^{o}F$)* and where the line is exposed to a range of wind speeds, directions, and tension.

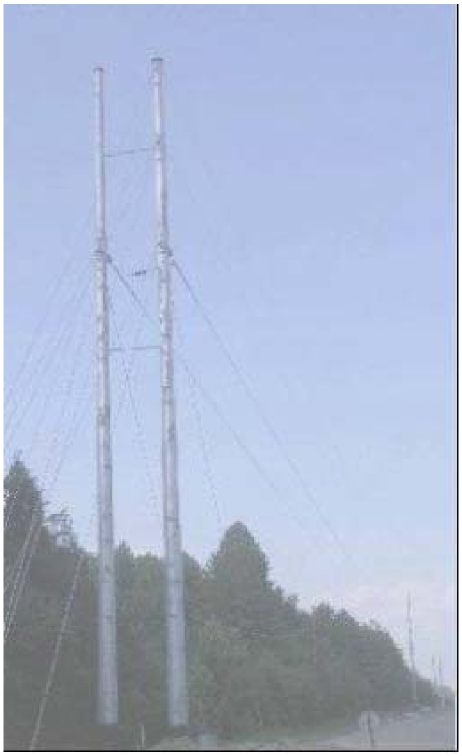
ORNL built a fully instrumented low-voltage test line to evaluate the high-temperature operation of ACCR conductors. The instrumentation includes mechanical tension, full weather station with anemometer, voltage, current, laser sensor to measure sag, and temperature thermocouples in multiple locations in the conductor and in all accessories, Figure 1.

This report summarizes the ACCR 477 conductor installation, testing and analysis at ORNL as well as post thermal cycling evaluation.

Aerial view of the line



Conductor cross section



Towers

Figure 1- View of the ORNL test line and conductor cross-section

2- Installation and Conductor Stringing

2-1 Overview

A four span test line was constructed on the grounds of the Oak Ridge National Laboratory in Oak Ridge, Tennessee, as a part of a Department of Energy program. Oak Ridge National Laboratory subcontracted the line engineering and construction to the Tennessee Valley Authority, (TVA). The test line (Figure 2) consists of 2, 600 feet (183 meters) spans between a steel suspension pole and two guyed dual steel dead end poles. The test conductor forms a loop over two spans connected to a DC power supply located at one end of the line. Thermocouples were installed along the test conductor and on the dead ends, suspensions and splices to measure the temperature of these components during and after periods of high temperature operation.

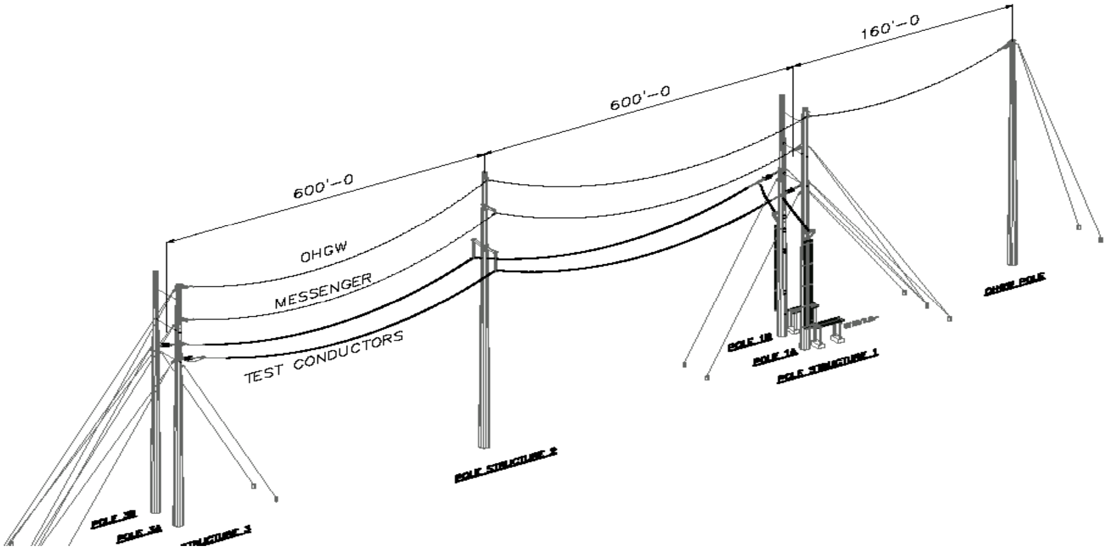


Figure 2- Line layout and CAT-1 system

2-2 Installation details:

The installation of the 477 ACCR follows the IEEE 524 installation guideline for overhead transmission conductors. The only conductor stringing method recommended is the tension method. It is important that bending of the composite conductor during installation be carefully planned to avoid damaging the composite core. The combination of bending and tension could damage the conductor if it exceeds the allowable core strength. Therefore stringing blocks and bull wheels were selected to keep the stringing loads below the conductor core strength. The crew used 28" diameter stringing blocks and 36" diameter bull wheels diameter to meet such criteria; Table 2. Lined blocks are recommended for use with ACCR. Cable spools around which the conductor is wrapped must have 40" diameter to avoid core damage. Other installation procedure and hardware used were very similar to that used for ACSR. PLP DG- Grips were used to pull the conductor to sag and to install full tension splices.

Sagging procedures of ACCR conductor are very similar to that of ACSR. During installations of this type of conductor, a dynometer was used to verify the final sag tensions of the conductor. By using a chain hoist and a dynometer between a temporary conductor grip and the tower structure, the final sag tension was set. Sufficient length of conductor was provided to install the permanent Alcoa dead end. The conductor grip was placed on the conductor at least 12 to 15 feet from the connection point to the insulator string. After the final sag tension was set, the dead ends were installed onto the ACCR. With the initial placement of the conductor grip at 12 to 15 feet, this allowed enough slack in the conductor to maneuver it and apply the dead end assembly.

Table 1- Installation Equipment and Procedure

Installation Equipment	ACSR	ACCR
Stringing blocks	Yes	Yes (28")
Bull wheels	Yes	Yes (54")
Drum Puller	Yes	Yes
Sock splice	Yes	Yes
Conductor grip	Any	Distribution grips, DG
Cable spool	Yes	Yes (48" drums)
Cable cutter	Yes	Yes
Reel stands	Yes	Yes
Grounding clamps	Yes	Yes
Running ground	Yes	Yes

Installation Procedure	ACSR	ACCR
Cable stringing	Tension/ slack	Tension
Sag tensioning	Any	Line of sight-Dynometer
Dead ending	Any	DG grips with chain hoist
Clipping	Any	Any

The following images and those under the next section are typical examples of the installation details

Figure 3- Conductor stringing

Figure 4- Sagging with chain hoist and dynometer

2-3- CAT-1 Instrumentation:

A CAT-1 system with weather station was installed on one of the dead end structures to monitor the conductor tension and weather conditions (temperature, wind speed, and direction) at one-minute intervals. Conductor tension was measured by the CAT-1 load cells, see Figure 5. The CAT-1 system includes an anemometer to measure wind speed and direction and a net radiation sensor to measure ambient temperature and solar radiation. Data acquisition was done at 1minute rate for all channels.

The CAT-1 main unit is in a NEMA-enclosed, solar powered, data acquisition and processing unit. Net Radiation Temperature, (NRT), was measured by the net radiation sensor, (NRS).

5-a Load cell to monitor tension

5-b CAT1 system

5-c Net radiation sensor, Measures no - load conductor temperature and solar radiation

Figure 5 CAT 1 System hardware

2- 4 Conductor and Accessories Temperature Measurements:

Temperature was measured using thermocouples mounted at various locations along the span, including ones directly touching the composite core and the conductor surface. Additional thermocouples were mounted on all accessories.

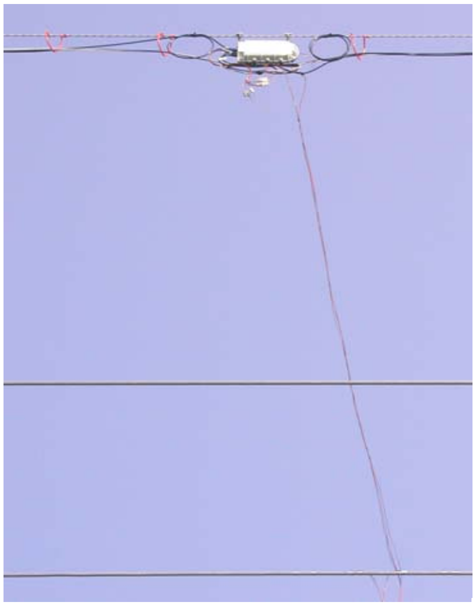


Figure 6- Thermocouple enclosure

A separate data acquisition system was used to collect the information from the thermocouples. To accommodate the multiplicity of points along the conductor and withstand the accumulated voltage drop, many fiber-connected, isolated measurement nodes were used. A thermocouple measurement node is fabricated using a multiplexer (ICPCON I-7018) and a RS-485-to-fiber modem (B&B FOSTCDR). Up to eight thermocouples are monitored per node. The node requires 120 VAC power and is data connected through a duplex fiber optic network. The multiplexer, fiber modem, and a power supply are housed in a Preformed Line Product COYOTE^{R} RUN T enclosure.

2-5 Controls

The line was operated under constant either current and / or constant conductor temperature with thermal cycles lasting from less than one hour to several days. The circuitry needed for controlling the 2MW power supply via software and analog to digital modules was built and installed. Also, a lower panel was added to permit remote control (in the instrumentation trailer) of the power supply's reset, contactor, and DC circuit. Previously, these were manually controlled at the power supply trailer only.

The power supply has a dual rating of 400 Vdc and 5000 amps or 600 Vdc and 3750 amps. The input voltage to the power supply is 4160 V, 3-phase. A dry-type ABB transformer is used to step down the voltage from a 13.8 KV distribution line.

2-6 Accessories:

Two types of full tension connectors were installed; a compression type made by Alcoa and a formed wire type made by Preformed Line Products, see Figures 7 to 9. The following is a list of all the accessories:

- Two ALCOA compression dead ends; part # B9085-A; those dead ends consist of both direct core gripping parts and conductor gripping sleeve.
- One ALCOA full tension splice part# B9095-A; it has the same design as the dead end for direct core gripping..
- Two THERMOLIGN^R PLP Suspensions, part # TLS-0101-SE
- Two PLP THERMOLIGN^R Dead Ends, part# TLDE-0104.
- One PLP THERMOLIGN^R Splice, Part #TLSP-0104.
- Six Alcoa all aluminum terminal connectors; Part# B9102-A
- Four Alcoa Stockbridge dampers; part # 1704-7.

Figure 7- THERMOLIGN^R Suspension

Figure 8- Installation of Alcoa compression splice.

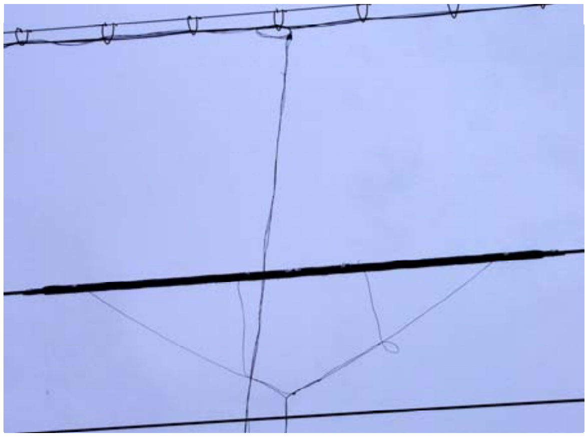


Figure 9- Installed PLP THERMOLIGN^{R} Splice

3- Thermal Cycles and High Temperature Exposure:

The 477 conductor was thermally cycled from May 2003 to October 2003 between ambient and over 200^{0} C for more than 200 hours under a wide range of weather and load conditions, Table 2. Figure 10 shows the composite conductor core temperature during a typical thermal cycle in temperature control. The temperature is maintained at 210-240 C by controlling the current from 1000 amps to 1200 amps while the wind fluctuates between 0 fpm and 15 fpm.

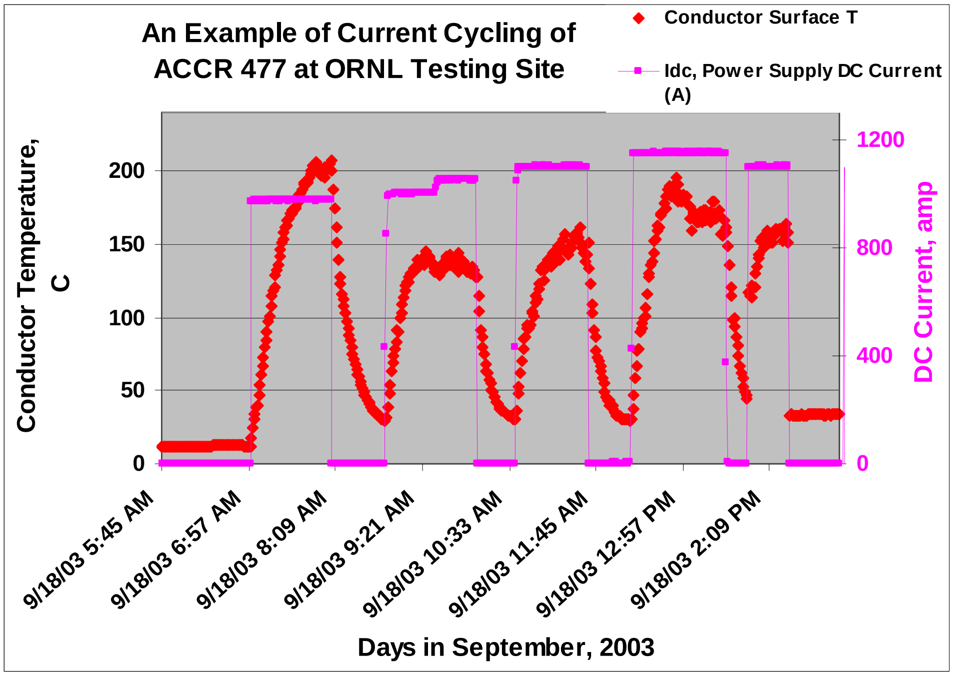


Figure 10- shows an example of thermal cycling in one day at ORNL test line

Table 2- Summary of Thermal Cycling of ACCR 477 at High Temperature

Date	#Cycles	Total	Hours	Total Run	Nature of cycle	Maximum
	Per day	Cycles	Per day	Hours		Current, amp
5/1/2003	1	1	10	10	Current controlled	1295
5/2/2003	1	2	7	17	Current controlled	992
6/2/2003	1	3	12.5	29.5	Current controlled	1177
6/4/2003	0	3	11	40.5	Current controlled	1060
6/5/2003	0	3	3	43.5	Current controlled	1053
6/9/2003	0	3	12	55.5	Current controlled	1057
6/10/2003	0	3	11.5	67	Current controlled	1031
8/27/2003	1	4	2.5	69.5	Current controlled	975
9/8/2003	5	9	5	74.5	Current controlled	1033
9/11/2003	5	14	10	79.5	Current controlled	1057
9/16/2003	4	18	14	83.5	Current controlled	1052
9/17/2003	7	25	21	90.5	Current controlled	1102
9/18/2003	5	30	26	95.5	Current controlled	1153
9/19/2003	8	38	34	103.5	Current controlled	1126
9/23/2003	8	46	42	111.5	Current controlled	1152
9/24/2003	7	53	49	118.5	Current controlled	1153
9/25/2003	8	61	57	126.5	Current controlled	1201
9/26/2003	8	69	65	134.5	Current controlled	1191
9/29/2003	8	77	73	142.5	Current controlled	1292
9/30/2003	7	84	80	149.5	Current controlled	1290
10/1/2003	4	88	84	153.5	Current controlled	1275
10/2/2003	8	96	92	161.5	Current controlled	1291
10/3/2003	8	104	100	169.5	Current controlled	1401
10/7/2003	1	105	(7hours/100 C)	176.5	Current controlled	861
10/13/2003	1	106	10	10	Temperature controlled	1172
10/14/2003	1	107	5	15	Temperature controlled	1370
10/15/2003	1	108	10	25	Temperature controlled	1236
10/16/2003	1	109	10	35	Temperature controlled	1256
10/17/2003	1	110	10	45	Temperature controlled	1114
10/18/2003	1	111	10	55	Temperature controlled	1225
10/21/2003	1	112	8	63	Temperature controlled	1311
10/22/2003	1	113	9	72	Temperature controlled	1288
10/23/2003	1	114	6	78	Temperature controlled	1201
10/24/2003	1	115	10	88	Temperature controlled	1213
10/27/2003	1	116	6	94	Temperature controlled	1225
10/28/2003	1	117	6	100	Temperature controlled	1214

Thermocouples were installed along the length of the conductor in two different spans and at different radial positions going from the conductor surface to contacting the composite core, Figure 11. The thermocouples indicated that there were significant temperature differences along the axial location and moderate gradients along the radial position.

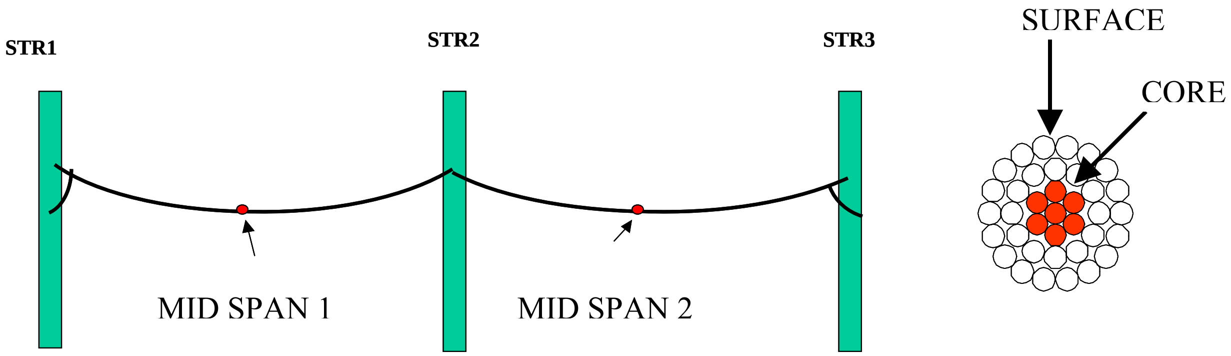


Figure 11- Thermocouples were positioned along the length and in different radial positions.

The radial gradient, when the conductor was above 200°C, was measured to fluctuate between 2°C and 15°C. In average, the radial gradient was about 8°C when the conductor was at 200°C, Figure 12a. Variation in wind speed and direction affected the magnitude of the radial gradient with greater wind speeds causing a larger gradient.

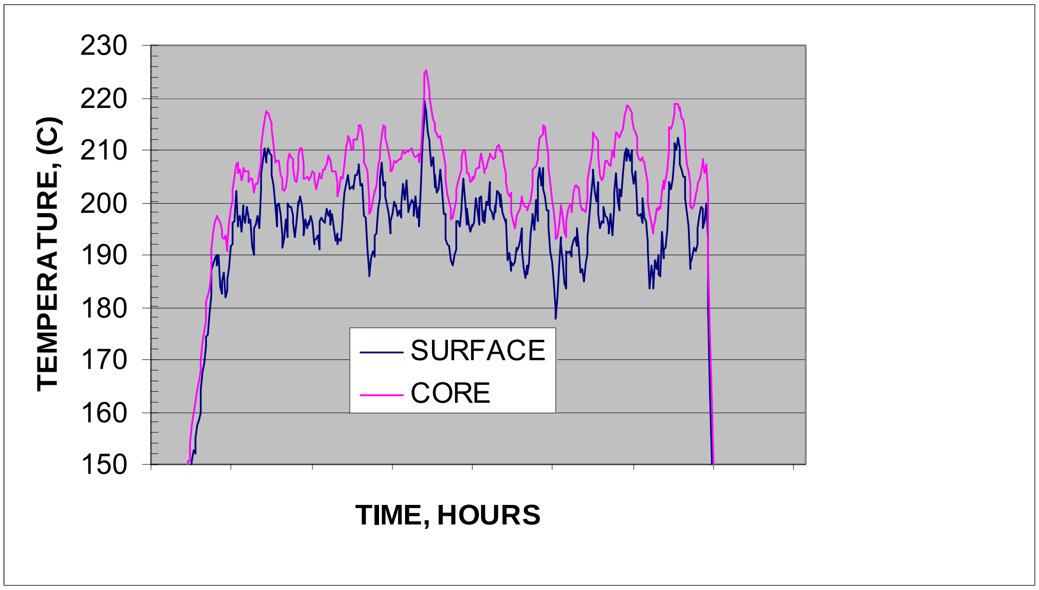


Figure 12- a- Temperature difference between conductor surface and core at mid span

Temperature fluctuation along the length of the conductor varied between 5^{o}C to 50^{o}C depending on wind conditions. Span 2 was more sheltered by trees than span1 and consistently experienced higher temperatures. The difference between span 1 and 2 was in average about 20^{o}C when the conductor was above 200^{o}C, Figure 12b. In some cycles the difference between span 2 and 1 was as high as 50^{o}C for a short period of time. As a result the maximum temperature in span 2 reached as high as 270^{o}C when the average temperature was at about 230^{o}C.

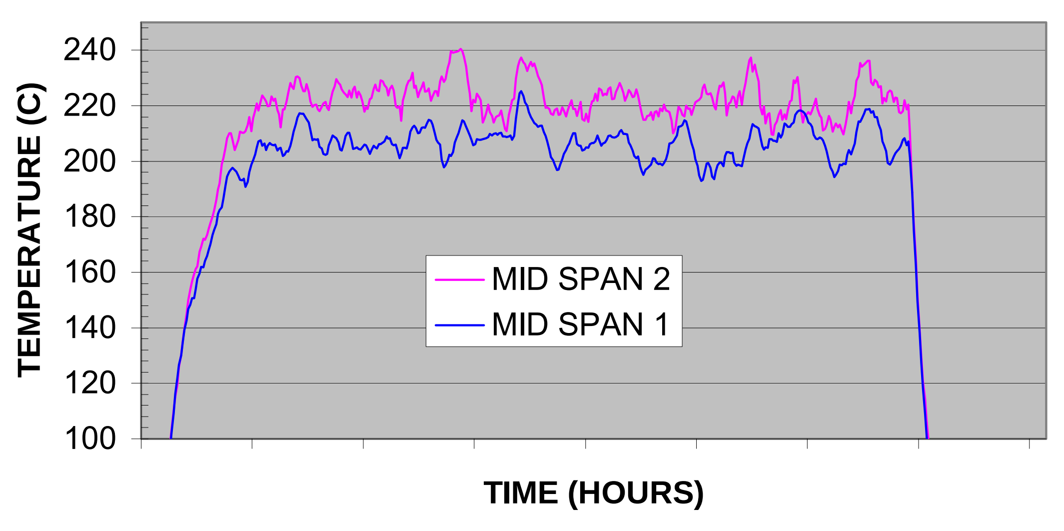


Figure 12- b An example of temperature difference along the conductor length.

4- Measured and Predicted Line Tension and Sag:

Sag was computed using the Strain Summation Method (which accounts for the full loading history) and the Graphic Method (Alcoa SAG-10). The main events, which cause permanent- elongation, were included (creep, low temperatures).

The calculated and measured tension and sag values are plotted in Figures 13 to 16 as a function of both conductor core and surface temperatures. The knee-point measured at about 80° C matches the prediction. It confirms the validity of the stress-strain, creep properties and thermo-elastic behavior of the conductor.

Figure 13 shows good agreement between measured and predicted tension in the range of 0^0 C and 250^0 C. The measured line tension lies in between values predicted using either the strain summation method or the graphic one. The predictions assumed a compressive stress of –1.45 Ksi in the aluminum after the knee point. The “October 28th” cycle was the last of over 100 cycles after the conductor experienced over 200 hours of high temperature exposure. It shows that the tension response remained predictable and stable after long thermal exposure and numerous cycles.

There is a small hysteresis observed between the heating and cooling cycles mostly due to variation in conductor temperature along the length of the line, and wire settling when passing through the knee point.

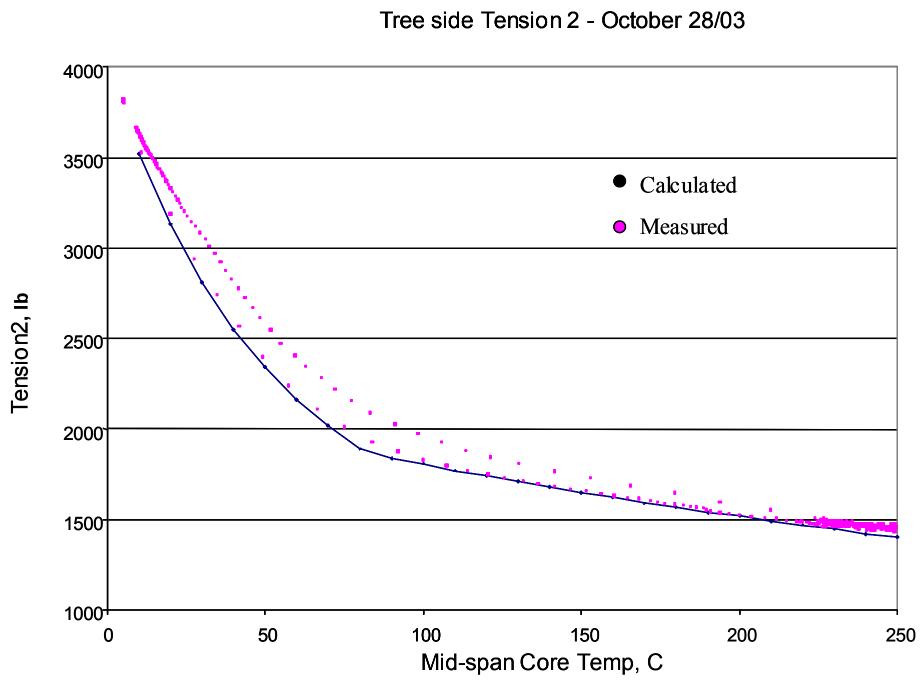


Figure 13- Good agreement between calculated and measured tension for the last cycle on October 28,2003. The Strain Summation method was used with a 1.45 ksi compressive stress.

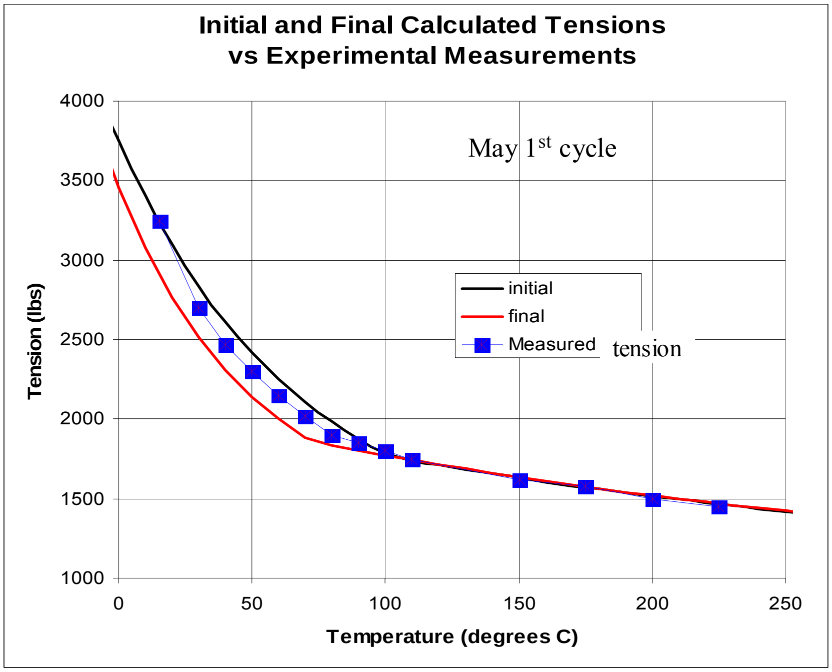


Figure 14- Initial and final tensions calculated using the SAG- 10^{TM} with 10 MPa (1.45 Ksi) compressive stress agree well with CAT-1 measured values.

Figure 13 shows the last high temperature cycle and Figure 14 shows both the first and last cycle. The measured conductor response was accurately predicted with the models using a –1.45 Ksi stress after the knee point.

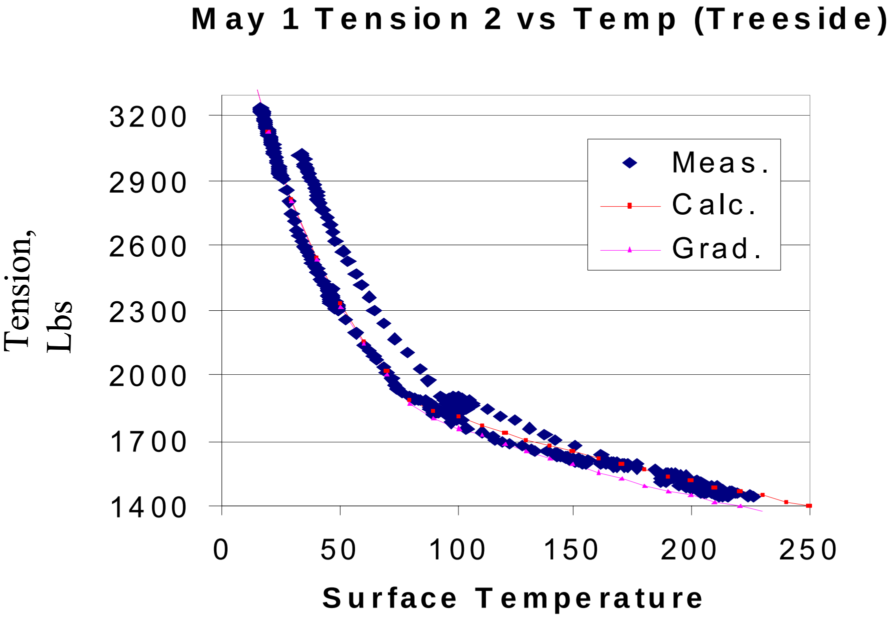


Figure 15- Measured vs. calculated tension, using the Strain Summation method, as a function of conductor temperature.

Figure 16 shows the tree-side line sag vs. conductor core temperature. The sag was directly measured at the mid- span with a laser monitor. The sag measurements agree with those calculated from tension within 0.2 feet.

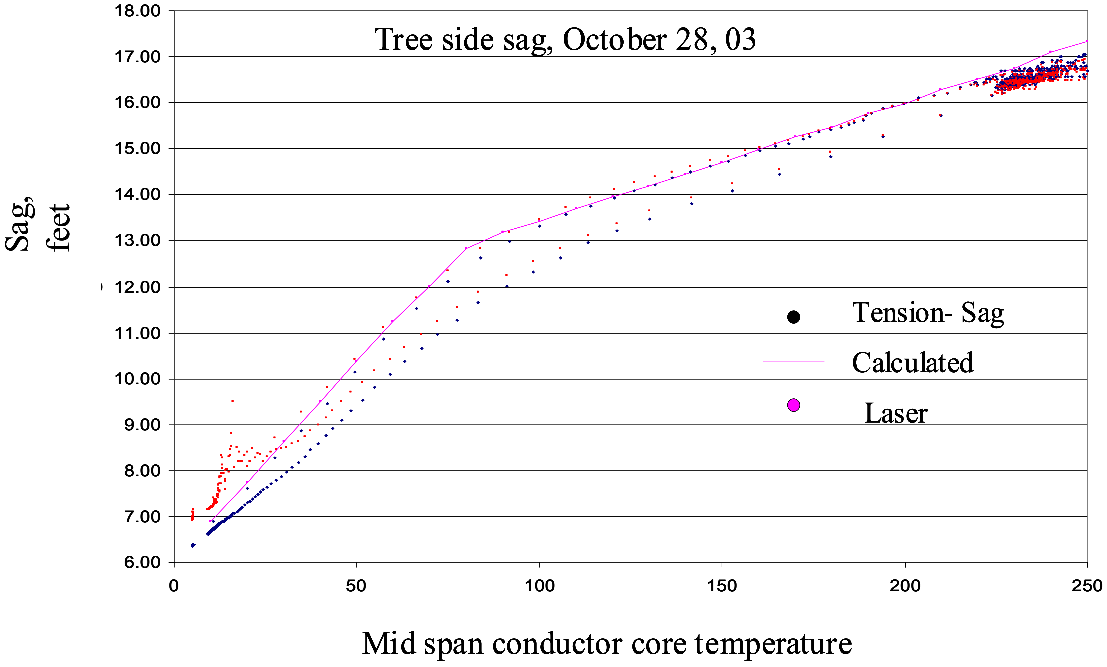


Figure 16- Measured Sags Compared with Those Calculated from Tension.

Summary:

Predicted sag agrees well with measured values in the range of 0^0 C to 250^0 C. The sag remained predictable after thermal cycling and long exposure to high temperature. There has been virtually no creep.

5- Accessories Response at High Temperature:

The accessories performed well during conductor thermal cycling and high temperature exposure; overall their maximum temperature was less than 120^0 C.

5-1 PLP Accessories:

Figure 17 shows that the inner reinforcing rods in the Thermolign^{R} Suspension had the highest temperature rise while the external housing had the lowest temperature rise, the neoprene insert did not see temperature higher than 100^{0} C.

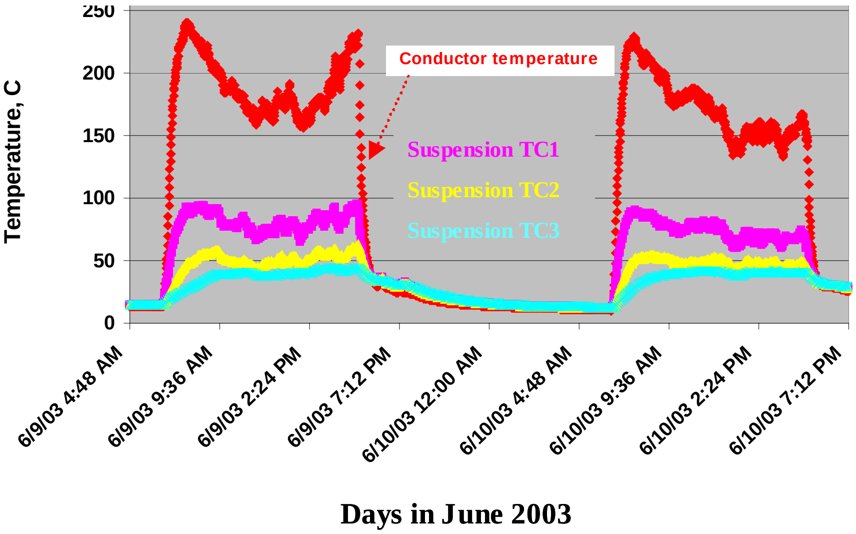


Figure 17- a shows the PLP THERMOLIGN^{R} suspension running at temperature < 100^{0} C when conductor was thermal cycled to above 200^{0} C

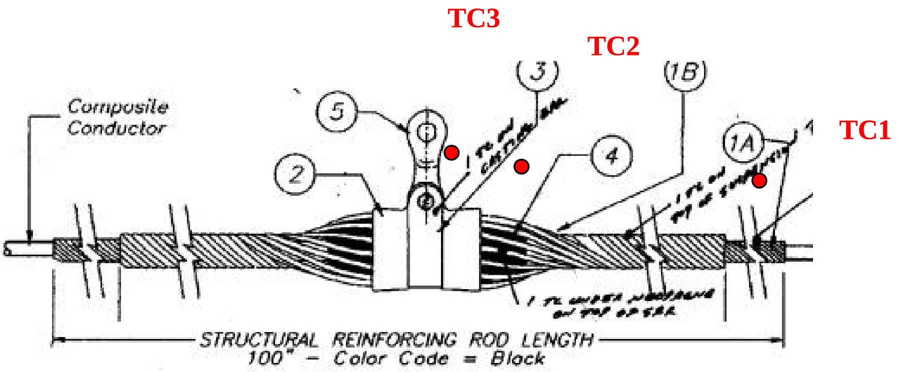


Figure 17-b PLP THERMOLIGN^{R} Suspension System thermocouples location (3 locations, TC1, 2 and 3) during current cycling.

The PLP THERMOLIGN^{R} dead end temperature profile along its length (6 locations- marked in red circles in Figure 18 shows a much lower temperature than that of the conductor, Figure 19. The inner rods maximum temperature was about 90^{0} C while the outer rods never exceeded 75^{0} C, Figure 20.

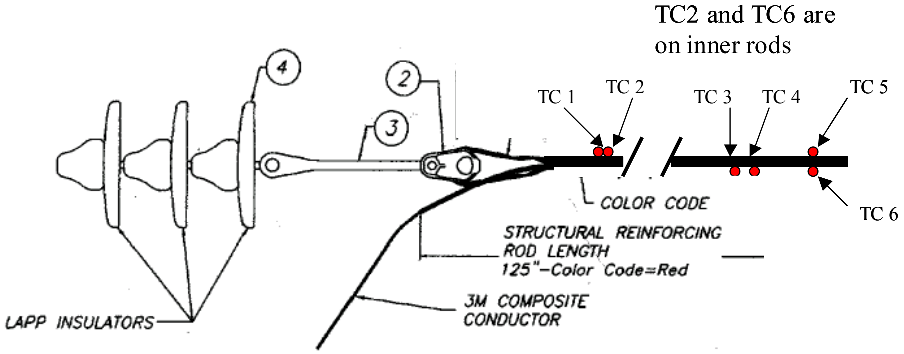


Figure 18-a- Location of thermocouples in red, TC's, on PLP THERMOLIGN^{R} dead end

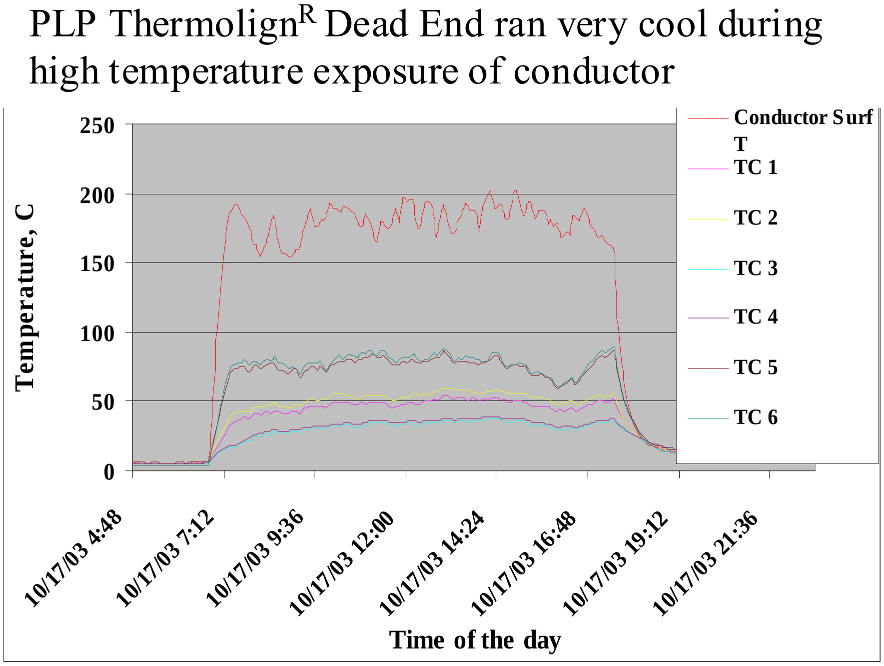

PLP Thermolign^{R} Dead End ran very cool during high temperature exposure of conductor

Figure 18-b An example of PLP THERMOLIGN^{R} Dead End temperature profile thermal cycling of conductor to 200^{0} C.

The PLP THERMOLIGN^{R} Splice temperature was monitored at 4 locations on both the inner stiffening rod and the outer one (Figure 19). The inner rod temperatures (PS1, 2) were slightly higher than those measured on the outer one- rod (PS3) and the inner center of the splice (PS4) where conductor segments come together (because of its proximity to the conductor); both splice rods ran cool (Figure 19).

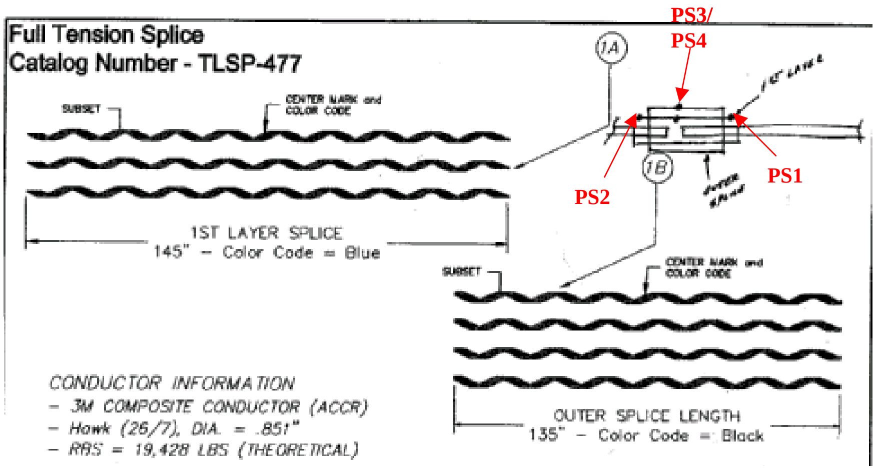


Figure 19- a- Thermocouple locations for temperature measurement of splice inner and outer rods.

PLP THERMOLIGN^R splice shows temperature gradient between inner and outer rods as shown in figure 19-b; two thermocouples were mounted on each rod.. Both rods ran much cooler than conductor, well below 100^0 C.

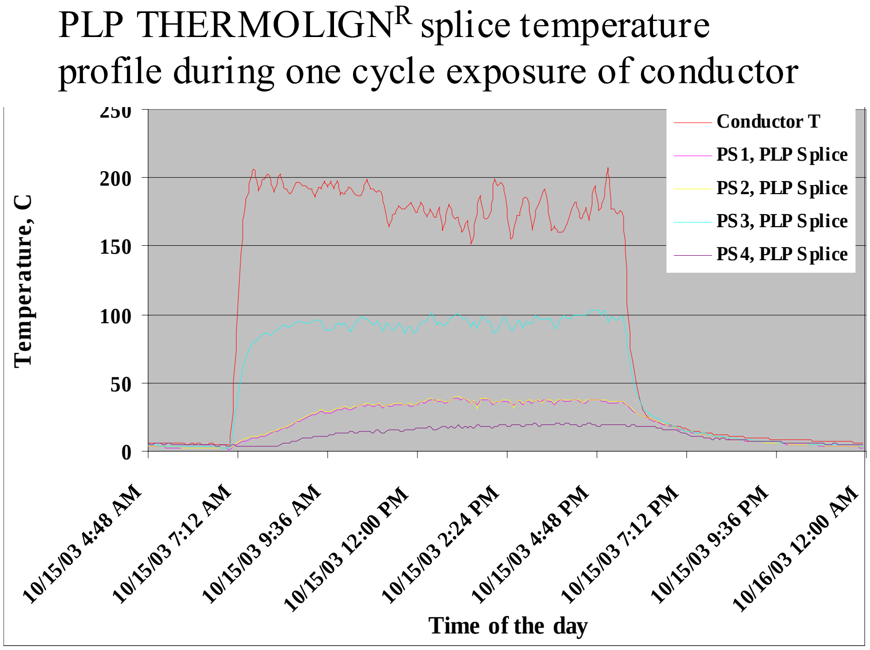


Figure 19-b An example of a single thermal cycle showing the PLP THERMOLIGN^R splice running very cool, temperature < 100^0 C when conductor was around 200^0 C.

To summarize all PLP accessories (dead end, splice and suspension) behaved normally during high temperature exposure of the ACCR 477 conductor, their maximum surface temperature was at or below 100^0 C.

5-2 AFL Telecommunications (Formerly Alcoa) Accessories:

Both AFL splices, dead end and terminal connector ran well below 100^0 C when conductor temperature was above 200^0 C as recorded by numerous thermocouples (five on dead ends, two on terminal connector and five on splice). Accessories temperature near the tapered mouth close to conductor was higher than at other locations but below 100^0 C (see Figures 20 to 22).

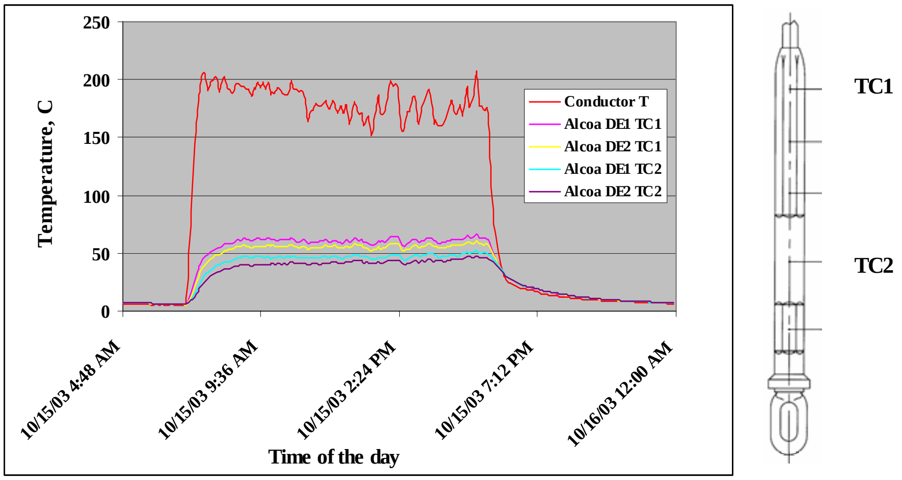


Figure 20- AFL compression dead ends temperature was below 70^0 C when conductor temperature was greater than 200^0 C

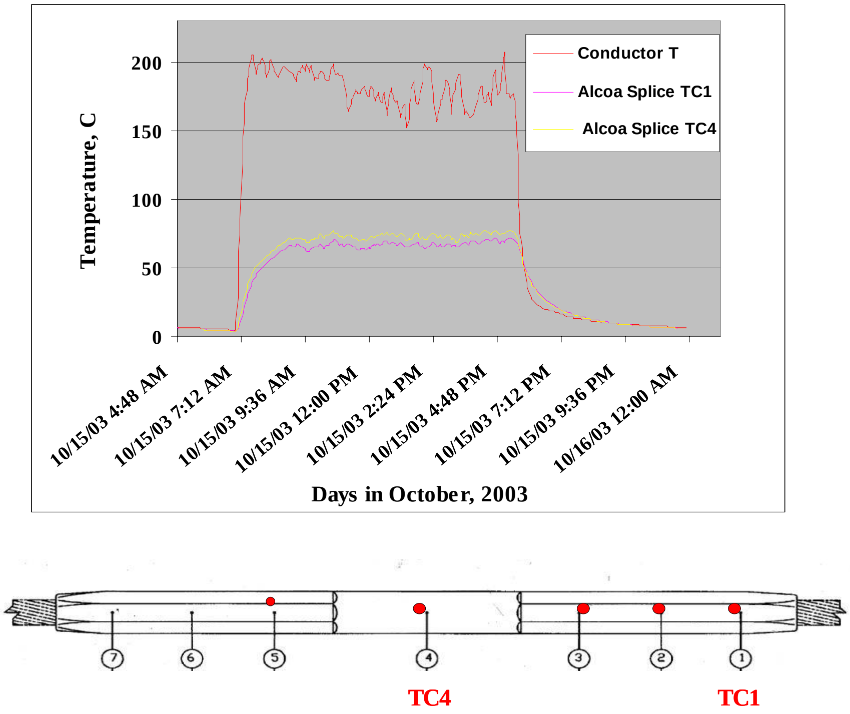


Figure 21 AFL Splice temperature during conductor cycling at around 200^0 C- Splice remained cool never exceeded 80^0 C

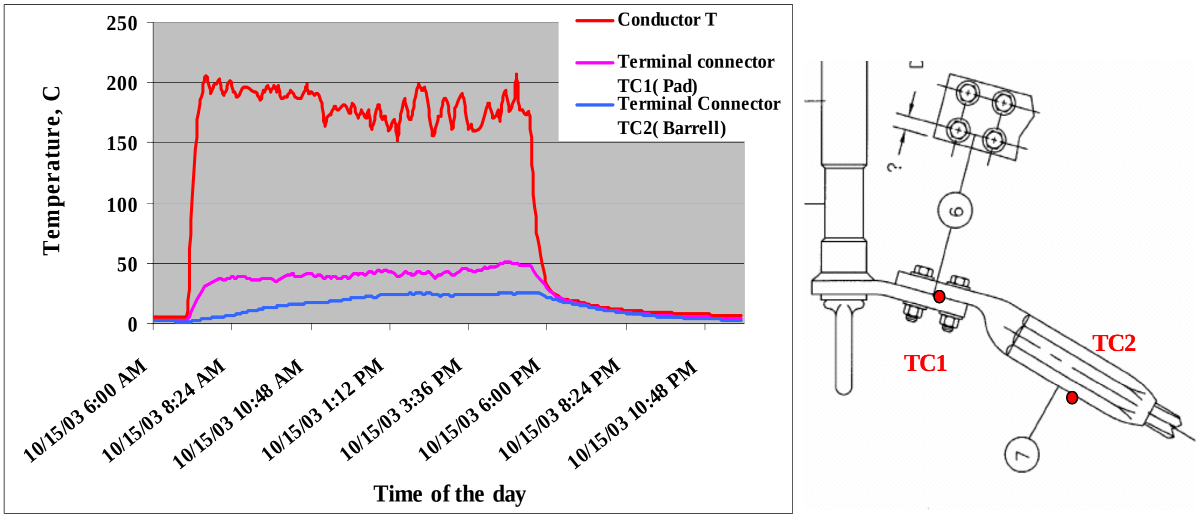


Figure 22- AFL compression terminal connector temperature less than 50 C when conductor temperature was greater than 200 ^{0}C

7- Ampacity and Thermal Rating of Conductor

The steady state version of the IEEE STD 738-1993 “Standard for Calculating the Current Temperature Relationship of Bare Overhead Conductors” was used to predict conductor current during thermal cycling. The model balances resistive losses, solar heating, convective and radiative heat losses. The data for current, wind speed and direction was used in the model; wind speed and direction were averaged over 60 minutes interval. Conductor emissivity ε = 0.347 was measured by ORNL using IR method. Both Figure 23 and table 3 show measured and predicted current. Table 4 lists values of parameters used in the model

Table 3 - Ampacity Rating Conditions and Data

Conductor temperature, C	Ambient Temperature, C	Wind speed, f/s	Wind angle, degrees	Measured Current. Amp	Computed current, amp
196	14	5	3	1004	1011
145	16	7	9	981	1011
119	18	8	9	994	978
162	20	9	9	1098	1120
223	25	4	19	1135	1160
162	26	4	20	986	1015
203	17	4	13	1050	1065
164	20	6	15	1050	1078
169	27	5	22	1047	1076
233	15	0	27	1049	1063
174	26	4	24	1050	1075
222	19	0	23	1025	1029
186	25	3	18	1025	1008
235	19	0	9	1024	1057
157	30	8	10	999	1032

Conductor temperature was used as input to the model along with other variables of Table 4. The agreement between model and measurements is good.

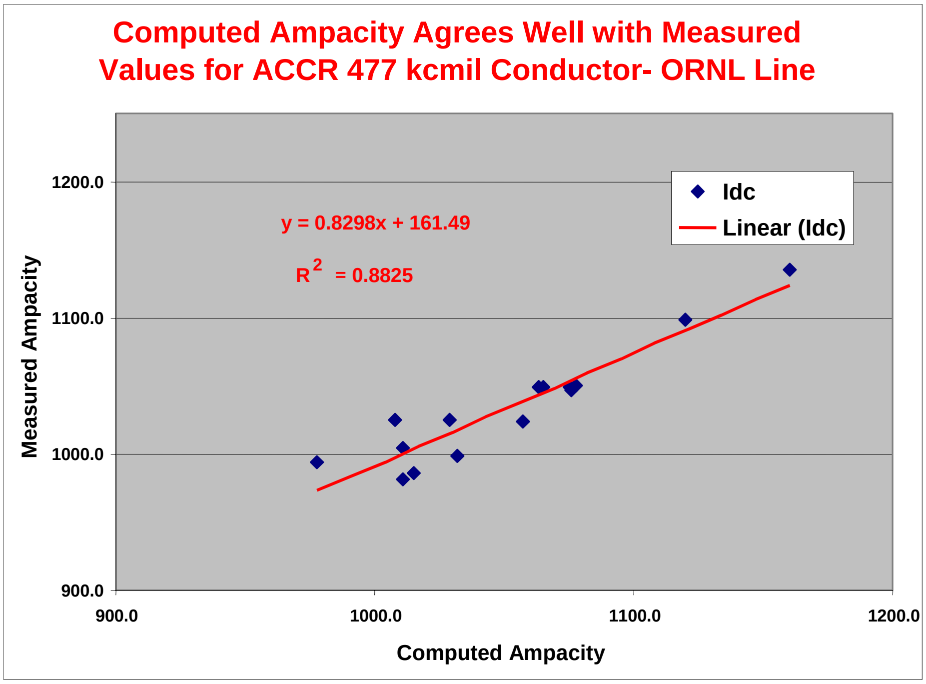


Figure 23- Predicted *vs.* Measured Steady State conductor current / rating

Emissivity		0.35
Solar Absorbtion		0.50
Conductor Elevation	ft above sea level	800.00
latitude	degrees	30.00
Zc		180.00
Sun Altitude	degrees	54.00
Theta	radians	1.57
density air	lb/ft^3	0.0765
Absolute Viscosity Air	lb/h-ft	0.0433
Thermal Conductivity Air	W/ft.degreeC	0.01

In summary the IEEE model predicted conductor current agrees reasonably well with that measured during thermal cycling at ORNL test line. The ACCR 477 conductor was rated at 1169 amps for continuous operation at 210^0 C and 1266 amps for emergency at 240^0 C using the model and 40^0 C ambient temperature, 2 f/s wind speed, emissivity & solar absorption of 0.5 at Sea Level. Thermal cycling history reported in Table 2 shows that the conductor was exposed to a maximum current in excess of 1350 amps without any degradation or damage, see Section 8 for details.

8- Post ORNL Conductor and Accessories Evaluation

The following tests & measurements were carried out on the conductor and accessories after thermal cycling at ORNL:

8-1 Conductor tensile tests:

Three samples from the "free-span" conductor were terminated using cast-resin terminations. Clamps were used to preserve the as-received position of the conductor layers until the resin cured. The sample preparation method ensures that the laboratory tensile test loads each conductor strand in the same manner as a field overloads, and thereby measures the in-service conductor strength. Free conductor between the end fittings is 20 feet (6 meters).

The 1999 Aluminum Association guide for conductor stress-strain testing was followed with the exception of special values for the elastic properties of the metal matrix composite (MMC) core were used instead of values for steel core used in ACSR conductors. The core strand from another sample is used to measure core stress-strain, and determine the elastic properties of the composite conductor.

The results show that the conductor maintained its strength after thermal cycling at above 200C. The average of five measurements is 109 % RBS as shown in Table 3.

Table 5- Conductor test data

Sample	Breaking load, Lbs	% RBS	Failure Mode
04114T1	20,710	106	All strands fractured in the gage section
04114T2	19,860	102	All strands fractured in the resin fitting
04114T3	20,800	107	All strands fractured at the resin fitting

Stress- Strain-conductor	20,350	104	Mid span break, all strands failed
Stress Strain-Core	12,910	111	Mid span break, all strands failed

8-2 Conductor Stress-strain:

Stress-strain results are similar to results from the same conductor prior to the field test. The principal difference is that creep during the 30% load hold phase is less on the field sample, apparently because the field loads caused the initial creep to be removed from the conductor as shown in Figures 24 to 26.

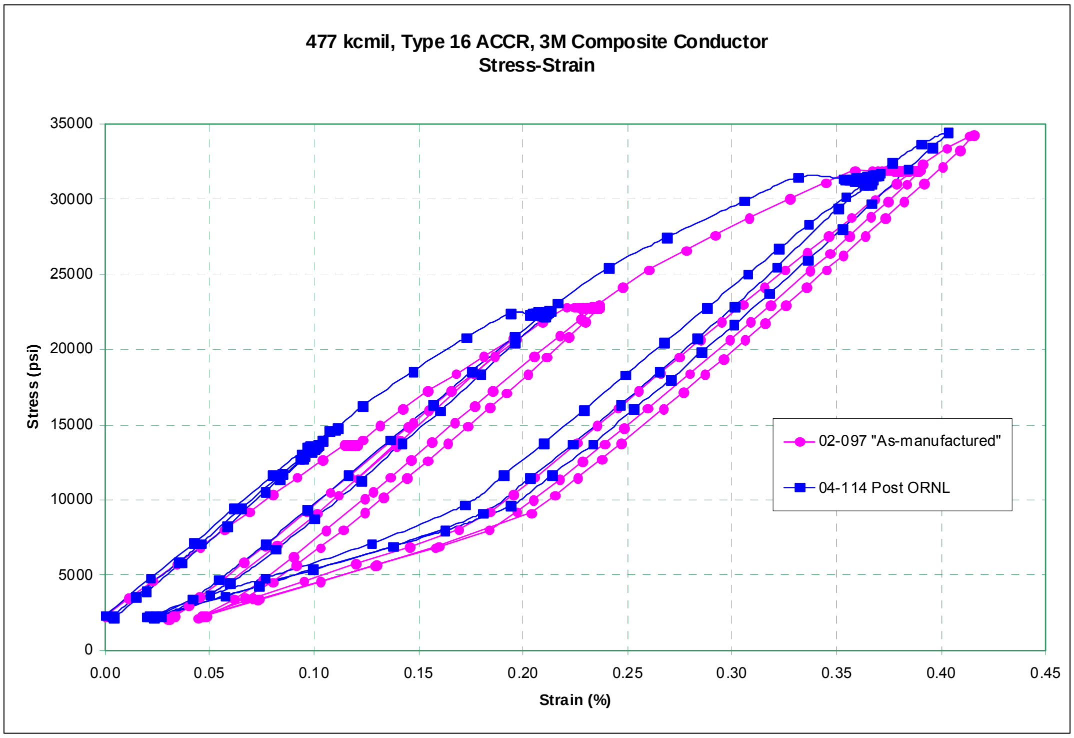


Figure 24- Plot of raw core stress-strain data recorded during conductor stress-strain test (blue),

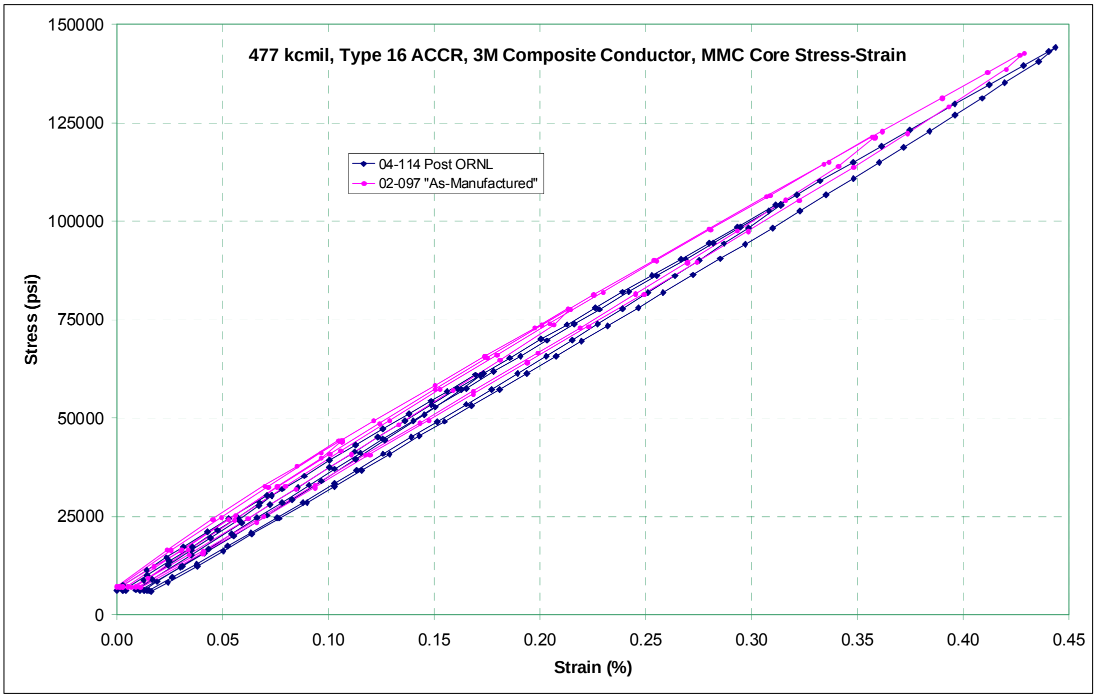


Figure 25- Core stress-strain shows essentially no change due to field test

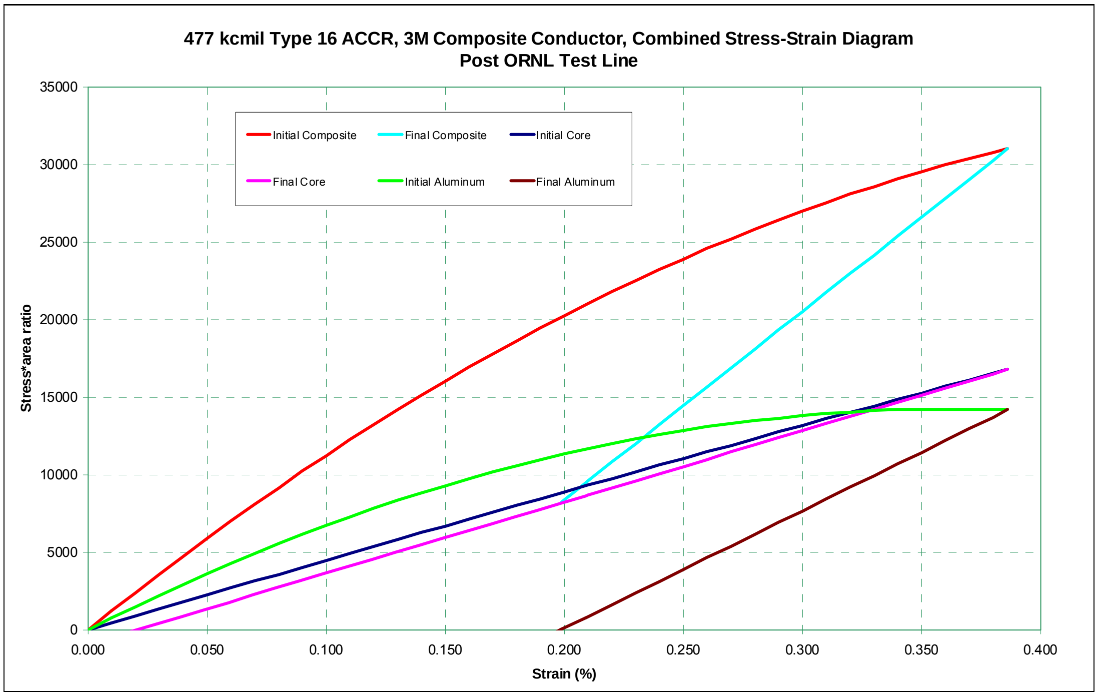


Figure 26- Combined stress- strain plot

8-3 Conductor resistance test:

Welded equalizers were installed at each end of a 19-foot long sample from the free-span section. A second set of voltage equalizers in the form of tightly wrapped solid copper strands are applied nominally 20 feet apart in the test section. The sample is placed on a flat surface, and pulled with sufficient tension to remove any residual curvature in the conductor. Tension was about 200 – 300 lb. A digital low-resistance Ohmmeter was used to make a 4-wire resistance measurement for the conductor section between the two voltage equalizers. A digital multi meter was used to verify the sample was electrically isolated (see Figure 27).

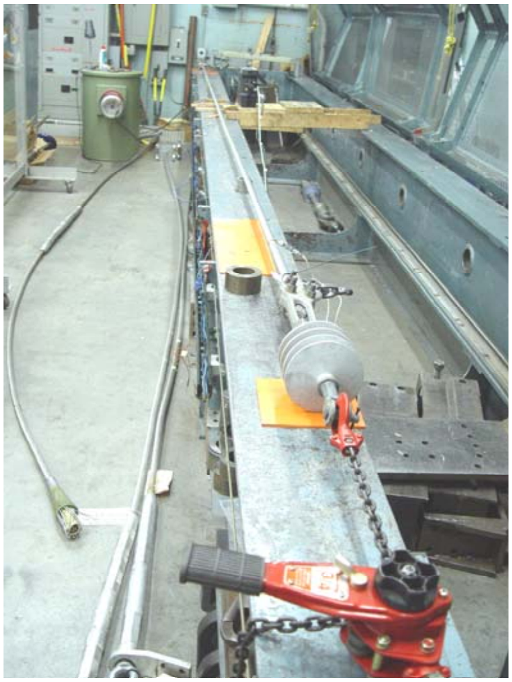


Figure 27- Resistance measuring set up and sample

Resistance of a 19 ft test section was measured. Readings were repeated later in the day as noted below. The average of all readings is 0.1834 Ω/mile at 20° C. The published value is 0.1832 Ω/mile at 20° C, very close to the measured value.

8-4 Connector tensile tests:

8-4-1 Alcoa compression accessories

Two dead-ends were provided with cast resin fittings at free ends. The procedure preserves the "as received" position of the conductor components, and thereby assures that the breaking strength is the same as existed when the samples were in service on the test span. Dead ends maintained their load carrying capability of 100% RBS or more (see Table 6 and Figure 28).

Table 6- Connector tensile tests

Sample	Breaking Load, Lbs	% RBS	Failure Mode
04114DE1	20,380	105	All strands fractured ~ 5" inside dead end
04114DE2	19,550	100	All strands fractured ~ 5" inside dead end

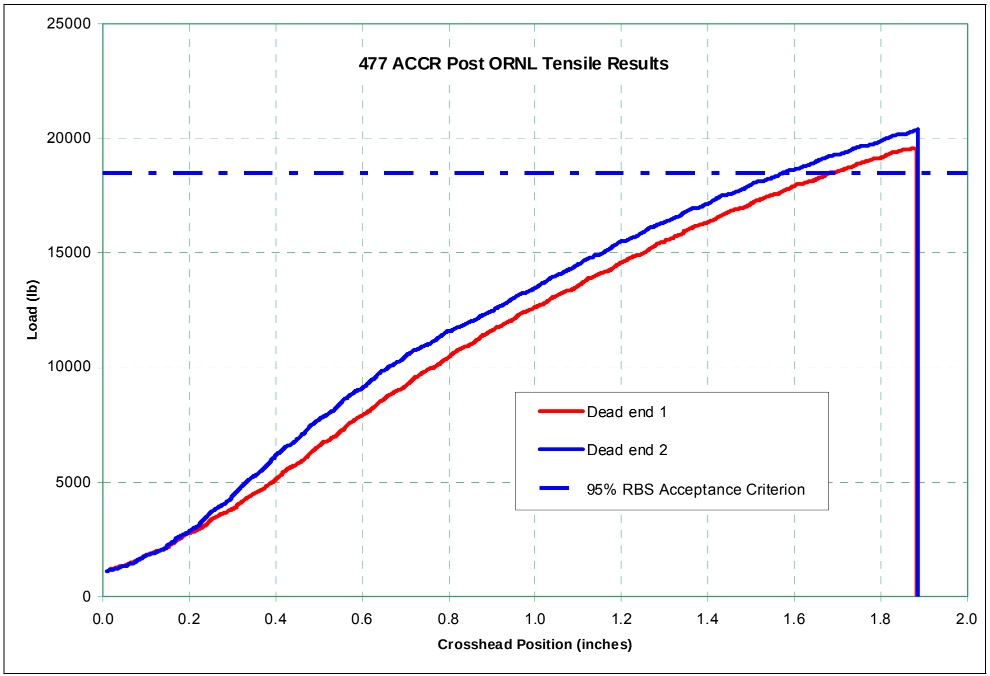


Figure 28 Connector tensile test plots

8-4-2 Alcoa (AFL Telecommunications) Connector Microscopic Examination:

Connector dissection (one dead): A milling machine was used to split the aluminum sleeve and reveal the internal components. Correct installation is verified by observing proper placement of the core grip, proper conductor preparation, and proper injection of inhibitor compound prior to compression

The dissections and inspections showed good workmanship for core and aluminum insertion depth, component placement, and the crimping operation. The center cavity was full of oxide inhibitor, and the distribution pattern shows that the injection was done correctly prior to the start of crimping. One discrepancy was noted: There is no evidence that the conductor was wire-brushed prior to splice installation. AFL instructions require wire brushing of the conductor OD only in cases where the connector is installed on weathered conductor. However, most field and lab experience is that failure to wire-brush new conductor can cause premature connector failure.

8-5 PLP Accessories:

The suspension taken down from the ORNL test line after thermal cycling was disassembled and conductor inside the suspension was tested for residual strength. It failed at 19,437 Lbs (100% RBS). The conductor failed 21” from center of suspension. Conductor samples and both the THERMOLIGN^{TM} Splice and Dead End were pulled in tension. Splice/ conductor combination failed at 19428 Lbs (100% RBS) in the conductor within the splice region. Two dead end samples with conductor were pulled to failure; they gave 19,157 Lbs (98% RBS) and 19,817 (102% RBS) Lbs respectively.

9- Summary

ACCR 477 conductor was installed successfully on the ORNL- PCAT line using commercial hardware and normal installation procedures. The conductor and accessories were thermally cycled from ambient to over 200^0C for several hundred hours, using DC power supply and as high current as 1200 amps. The measured sag matched the SAG-10 prediction. Data analysis shows that the measured conductor current agrees well with the IEEE thermal rating model predicted values. After de-installation the conductor and accessories were tested for residual strength and degradation. Residual strength exceeded 100% RBS and neither conductor nor accessories showed any signs of damage. Conductor resistance after cycling is equivalent to that of conductor not exposed to thermal cycling

10- Appendix

10-1 Conductor Specs

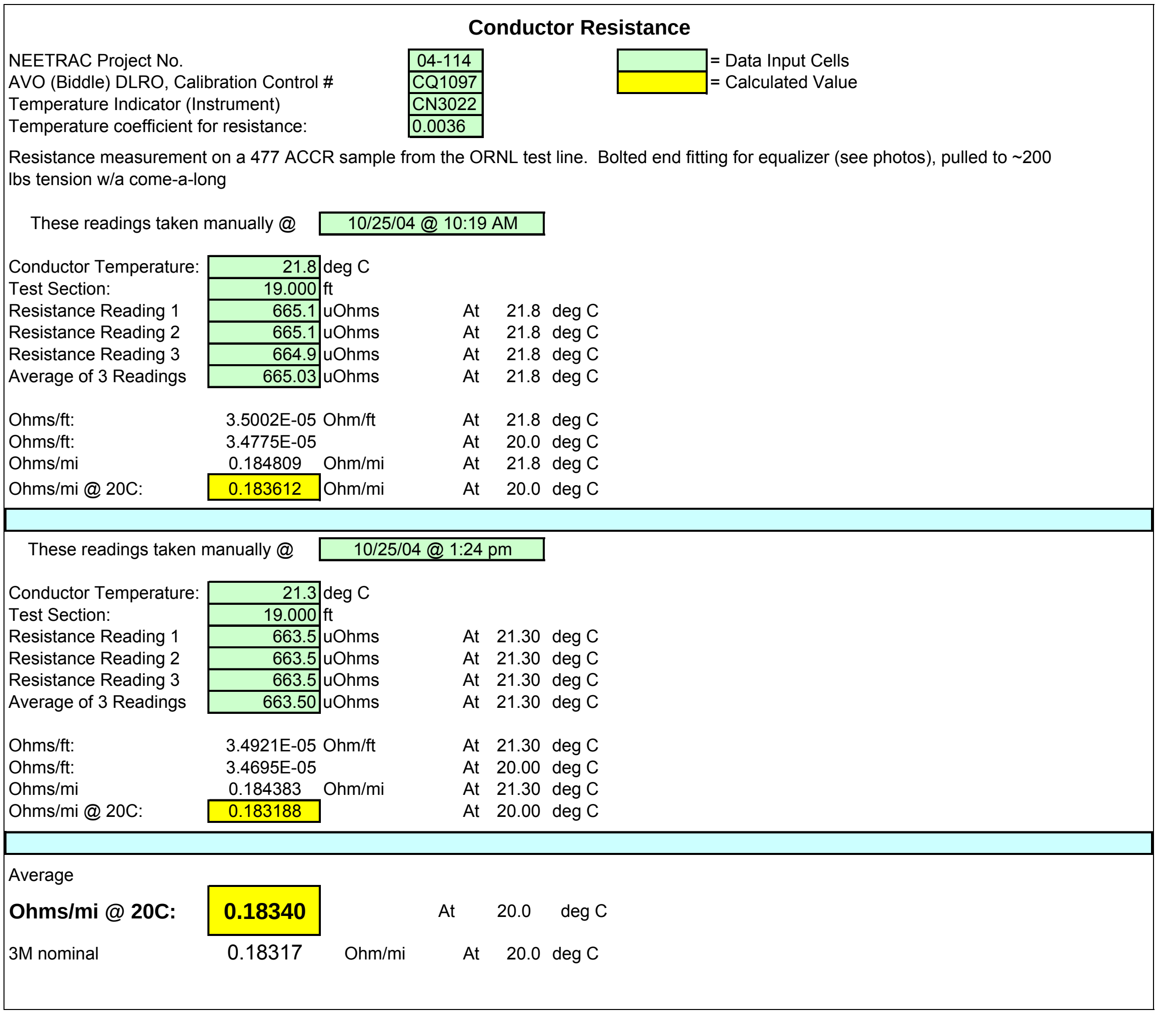
Conductor Physical Properties

Designation		477-T16
Stranding		26/7
kcmils	kcmil	477
Diameter		
indiv Core	in	0.105
indiv Al	in	0.135
Core	in	0.32
Total Diameter	in	0.86
Area		
Al	in^2	0.374
Total Area	in^2	0.435
Weight	lbs/linear ft	0.539
Breaking Strength		
Core	lbs	11,632
Aluminum	lbs	7,844
Complete Cable	000's lbs	19,476
Modulus		
Core	msi	31.4
Aluminum	msi	8.0
Complete Cable	msi	11.2
Thermal Elongation		
Core		6
Aluminum		23
Complete Cable		16
Heat Capacity		
Core	W-sec/ft-C	13
Aluminum	W-sec/ft-C	194

Conductor Electrical Properties

Resistance		
DC @ 20C	ohms/mile	0.1832
AC @ 25C	ohms/mile	0.1875
AC @ 50C	ohms/mile	0.2061
AC @ 75C	ohms/mile	0.2247

10-2 Conductor Resistance Data:



Conductor Resistance

NEETRAC Project No.	04-114	🟩	= Data Input Cells
AVO (Biddle) DLRO, Calibration Control #	CQ1097	🟨	= Calculated Value
Temperature Indicator (Instrument)	CN3022		
Temperature coefficient for resistance:	0.0036		

Resistance measurement on a 477 ACCR sample from the ORNL test line. Bolted end fitting for equalizer (see photos), pulled to ~200 lbs tension w/a come-a-long

These readings taken manually @ 10/25/04 @ 10:19 AM

Conductor Temperature:	21.8	deg C			
Test Section:	19.000	ft			
Resistance Reading 1	665.1	uOhms	At	21.8	deg C
Resistance Reading 2	665.1	uOhms	At	21.8	deg C
Resistance Reading 3	664.9	uOhms	At	21.8	deg C
Average of 3 Readings	665.03	uOhms	At	21.8	deg C
Ohms/ft:	3.5002E-05	Ohm/ft	At	21.8	deg C
Ohms/ft:	3.4775E-05		At	20.0	deg C
Ohms/mi	0.184809	Ohm/mi	At	21.8	deg C
Ohms/mi @ 20C:	0.183612	Ohm/mi	At	20.0	deg C

These readings taken manually @ 10/25/04 @ 1:24 pm

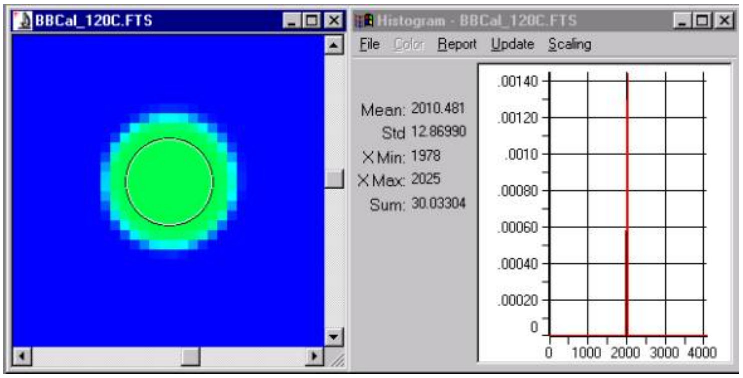
Conductor Temperature:	21.3	deg C			
Test Section:	19.000	ft			
Resistance Reading 1	663.5	uOhms	At	21.30	deg C
Resistance Reading 2	663.5	uOhms	At	21.30	deg C
Resistance Reading 3	663.5	uOhms	At	21.30	deg C
Average of 3 Readings	663.50	uOhms	At	21.30	deg C
Ohms/ft:	3.4921E-05	Ohm/ft	At	21.30	deg C
Ohms/ft:	3.4695E-05		At	20.00	deg C
Ohms/mi	0.184383	Ohm/mi	At	21.30	deg C
Ohms/mi @ 20C:	0.183188		At	20.00	deg C

Average

Ohms/mi @ 20C:	**0.18340**		At	20.0	deg C
3M nominal	0.18317	Ohm/mi	At	20.0	deg C

10-4 Emissivity Measurements:

Oak Ridge National Laboratory measured various 3M composite conductor emissivity using IR Imaging. A calibrated IR Camera and Mikron M305 Blackbody calibration source were used. Figures 29 shows the used hardware; the calibrated black body target was multiplied by various emissivity values until a good fit occurs with the conductor received signal (see Figure 30). Such fit yielded an average emissivity value of 0.345 within +- 2% (see Figure 31).



Mean: 2010.481
Std 12.86990
X Min: 1978
X Max: 2025
Sum: 30.03304

Figure 29- Calibrated IR Camera and Mikron M305 Blackbody calibration source used for measuring emissivity

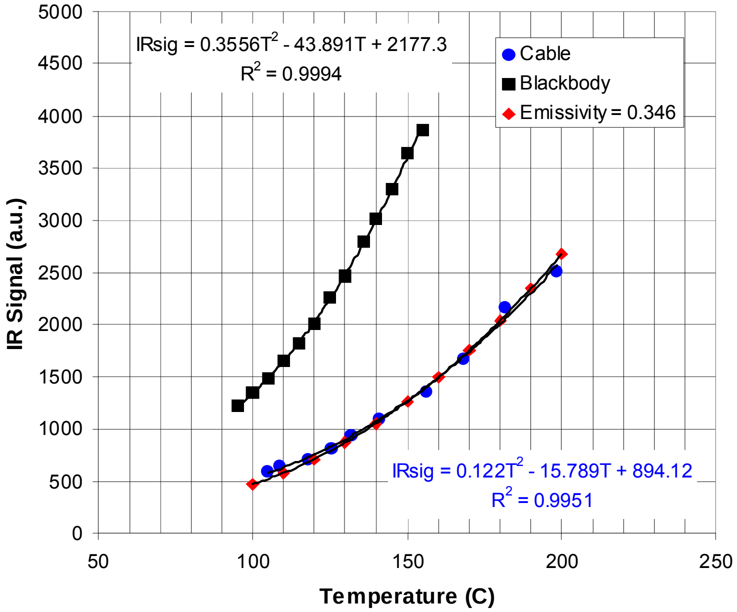


Figure 30- Conductor emissivity of 0.348 was determined using a black body signal matching

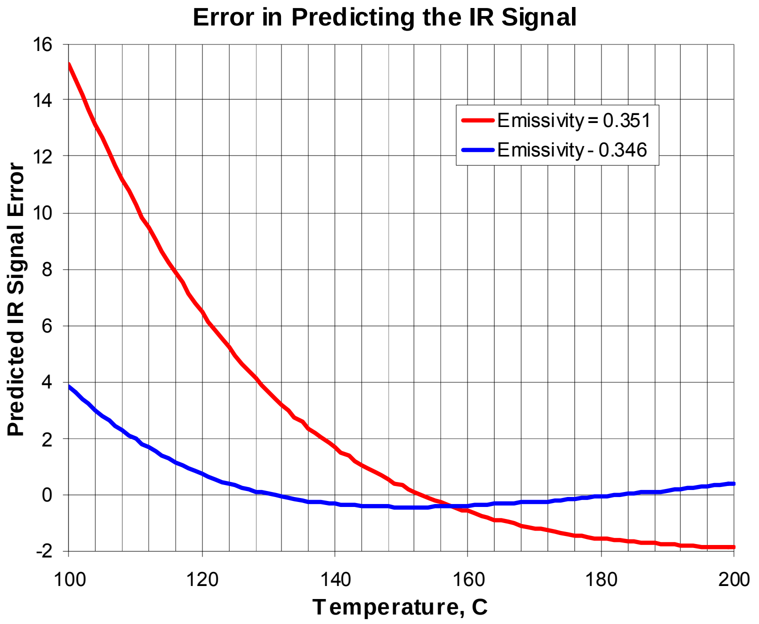


Figure 31- Signal error is < 1% in the temperature range 120 to 200 C with an emissivity value of 0.346

Appendix A.2

ACCR 795 Kcmil Report

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Composite Conductor Field Trial Summary Report: ORNL ACCR 795Kcmil

Field trial location	Oak Ridge, Tennessee, USA

Line Characteristics

Organization	Oak Ridge National Laboratory
Point of Contact	John Stovall, ORNL
Installation date	June 14, 2005
Conductor Installed	ACCR 795
Length of line	1,200 feet (356.7 meters)
Conductor diameter	1.108 inch, (28.1 mm)
Voltage	400 VDC
Ruling span length	600 feet, (183 meters)
Structure Type	Steel Poles
Instrumentation:	(1) Load cell (2) Current, voltage (3) Weather station (4) Sag (5) Thermocouples on conductor and accessories

Hardware

Suspension Hardware	Preformed Line Product, THERMOLIGN^{TM} SUSPENSION-TLS-0108-SE
Termination Hardware	AFL compression dead end, Part# B9178-B AFL compression splice, Part# B9095-B
Insulator type	Polymer
Dampers	Alcoa Dampers Part# 1707-13
Terminals	AFL terminal connector (jumper terminal), Part# B9102-B Transition plates, Part# ACP-E
PLP terminations	PLP THERMOLIGN^{TM} DEAD END, Part# TLDE-0114 PLP THERMOLIGN^{TM} SPLICE, Part# TLSP-0114 DG- 4553

Results and Measurements

Temperature- cycling from -5^{o}C to 240^{o}C using currents ranging from 0 to 2300 amps.
Tension-temperature data from 0^{0}C to around 240^{0}C
Measured and computed thermal rating

This material is based upon work supported by the U.S. Department of Energy under Award No. DE-FC02-02CH11111. Any opinions, findings or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the U.S. Department of Energy.

Table of Contents

Abstract:

Under DOE funding Agreement No. DE-FC02-02CH11111, Oak Ridge National Laboratory, ORNL, jointly with The Tennessee Valley Authority, TVA, installed a 795 kcmil ACCR conductor on ORNL high temperature test line on June 14, 2005. The line is 1200 feet (365 meters) long, and the ruling span is 600 feet (183 meters).

ORNL subjected the line to extensive thermal cycling and high temperature load using 400 V DC and currents from 800 to 2300 A. The conductor was thermally cycled from ambient to up to 240^0 C for about 1000 hours between September 13 and November 30, 2005 and over 600 hours operation continuously above 200^0 C under changing wind and ambient temperature conditions.

The measured conductor tension-temperature response agrees with predictive models. The measured current-temperature response agrees well with the predicted values, (IEEE 738 model).

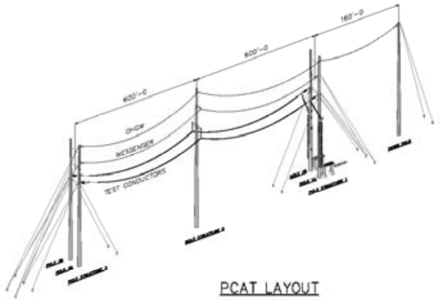
The accessories performed well during the high temperature cycling and ran at much cooler temperatures than the conductor. No visual changes were observed on the conductor and accessories. The conductor and accessories will be de-installed and tested when the thermal cycling is complete

1- Background:

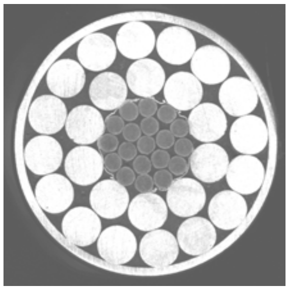
ORNL has built a fully instrumented low-voltage test line to evaluate the high-temperature operation of ACCR conductors by simulating numerous emergency cycles where the conductor temperature reached operating temperature up to 210^0 C under a range of weather and ambient temperature conditions.

The ORNL test line instrumentation includes a CAT-1 system for measuring conductor tension, ambient & solar temperature and weather. Multiple thermocouples were mounted at various locations on the conductor and all accessories.

This report summarizes the 795 ACCR conductor installation, thermal cycling and data analysis.



Arial view of the line



ACCR 795

Figure 1- ORNL test line view and conductor details

2- Installation and Conductor Stringing:

2-1 Overview:

A two span test line (from dead end to dead end) was constructed on the grounds of the Oak Ridge National Laboratory in Oak Ridge, TN, as a part of a Department of Energy program, Figure 1. Several sizes of ACCR composite conductors were installed and tested since then. ACCR 795 is the latest of such installations. The installation procedures used is typical of that used when installing ACSR. Tables 1 and 2 show the typical hardware and procedures used during installations and comparisons with ACSR installation hardware

2-2 Installation details:

The test line (Figure 1) consists of four 600 feet (183 meters) segments between a steel suspension pole and two guyed dual steel dead end poles. The test conductor forms a loop of two spans connected to a DC power supply station located on a trailer at one end of the line. Thermocouples were installed along the test conductor and on dead ends, suspension and splices to measure the temperature of these components during and after periods of high temperature operation.

Conductor was shipped to the installation site wound around wooden reels 84”x36” x44”. The installation followed the IEEE 524 installation guideline for overhead transmission conductors. Grounded stringing blocks were used at all the dead end structures.

Particular care was given to the stringing operation. The combination of bending and tension could damage the conductor if it exceeds the composite core allowable strength. Therefore stringing blocks and bull wheel were selected to keep the stringing loads well below the core strength. Table 1 specifies lined stringing blocks 28” diameter and a bull wheel of 54” diameter to meet such criteria.

The sagging procedure of ACCR conductor is similar to that used to install ACSR; a dynometer was used to verify the final tension of the conductor.

The following pictures show examples of some of the installation hardware.

Figure 2 PLP dead end installation using double 28” sheave at the first tower

Figure 3- An example of a Suspension System installed at middle tower

Figure 4 shows installed compression dead end and terminal connector

Figure 5 Conductor unwinding station

Figure 6 Thermocouples wiring for in-situ – temperature monitoring

Table 1- Installation Equipment

Equipment	ACCR
Stringing blocks	28" Suspension
Stringing blocks	60" roller array block- dead ends
Bull wheel	54"
Drum puller	Yes
Sock splice	Yes (no bands)
Conductor grips	DG grips
Cable spools	40" drum min
Cable cutter	Yes
Reel stand	Yes
Grounding clamps	Yes
Running ground	Yes

Table 2- Installation Procedure

Procedure	ACCR
Cable stringing	Tension
Sag tensioning	Dynometer, line of sight
Dead ending	Compression or Preformed.
Clipping	Thermolign suspension

2-3- PCAT-1 Instrumentation:

A CAT-1 system from The Valley group was installed on one of the dead end structures to monitor the conductor tension and weather conditions (temperature, wind speed, and direction). Two 10,000 pounds load cells were used for line tension. The CAT-1 system was equipped with an anemometer to measure wind speed and direction. Data acquisition was done at 1minute interval for all channels

The CAT-1 main unit is in a NEMA-enclosed, solar powered, data acquisition and processing unit, see figure 7. Net Radiation Temperature, (NRT), was measured by the net radiation sensor, (NRS).

7- A Load cell used to measure tension

7- B CAT-1 System

7- C Net Radiation Sensor Measures
No Load Conductor Temperature

Figure 7- CAT 1 System hardware

2-4 Conductor and Accessories Temperature Measurements:

A separate data acquisition system was used to collect the information from the thermocouples every minute, see example in Figure 8.. Thermocouples were mounted at various locations along the span on both conductor and all accessories. Both conductor surface and core temperatures were measured.

2-5 Controls:

The line was operated under either constant current and / or constant conductor temperature with thermal cycles lasting from one hour to several days each.
Multiple points along the length of the conductor were monitored this way using the installed thermocouples. To accommodate the multiplicity of points along the conductor and withstand the accumulated voltage drop, many fiber-connected, isolated measurement nodes were used. A thermocouple measurement node was fabricated using a multiplexer (ICPCON I-7018) and a RS-485-to-fiber modem (B&B FOSTCDR). Up to eight thermocouples were monitored per node. The node required 120 VAC power and was connected through a duplex fiber optic network. The multiplexer, fiber modem, and a power supply were housed in an enclosure.

The power supply used has a dual rating of 400 Vdc and 5000 amps or 600 Vdc and 3750 amps. The input voltage to the power supply is 4160 V, 3-phase. A dry-type ABB transformer was used to step down the voltage from a 13.8 KV distribution line.

2-6 Accessories:

Two types of accessories were installed; a compression type made by Alcoa (presently known as American Fujikura Limited, AFL) and formed wire type made by Preformed Line Products, PLP. The following specific parts were installed:

- Two ALCOA compression dead ends; Part # B9178-B
- One ALCOA full tension splice Part# B9095-B
- Four Alcoa jumper terminals (terminal connectors); Part# 9102-B

- Two transition plates, Part# ACP-E
- Two PLP THERMOLIGN^{TM,} DEAD ENDS, Part# TLDE-0114 (includes extension link and Thimble- Clevis)
- PLP THERMOLIGN^{TM} SPLICE Part # TLSP-0114
- Two THERMOLIGN^{TM} PLP SUSPENSIONS with Socket eye, Part # TLS- 0108-SE

3- Thermal Cycles and High Temperature Exposure:

3-1 Thermal cycles details:

The 795 Conductor was thermally cycled starting in September 2005, between ambient temperature and 200^0 C, sometimes above 240^{0}C, under wide range of weather and load conditions. Conductor surface temperature was measured at all locations while core temperature was measured at two positions on the mid span; see example of a single thermal cycle in figure 9. The conductor temperature dropped on rainy days by more than 40^{0}C. Figure 10 shows locations of the thermocouples used to measure both the conductor and accessories temperature. There were two thermocouples on each accessory, one to measure temperature at the tip of the accessory for the AFL compression accessories or at the inner rod for the PLP accessories). The second thermocouple measured the outer surface temperature for the compression accessories or outer rod temperature for the PLP accessories. Table 3 gives a summary of the cycles conducted from ambient to over 240^{0}C.

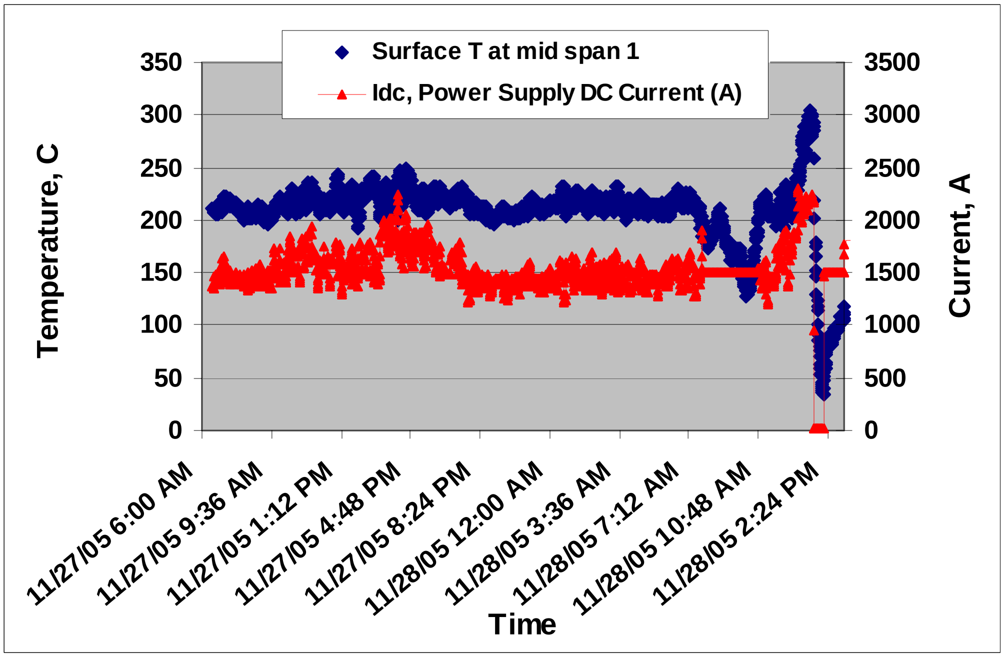


Figure 8 shows a single cycle at 200^0 C followed by a short cycle at 300^0C. Conductor's surface temperature dropped with rain on 11-28-05.

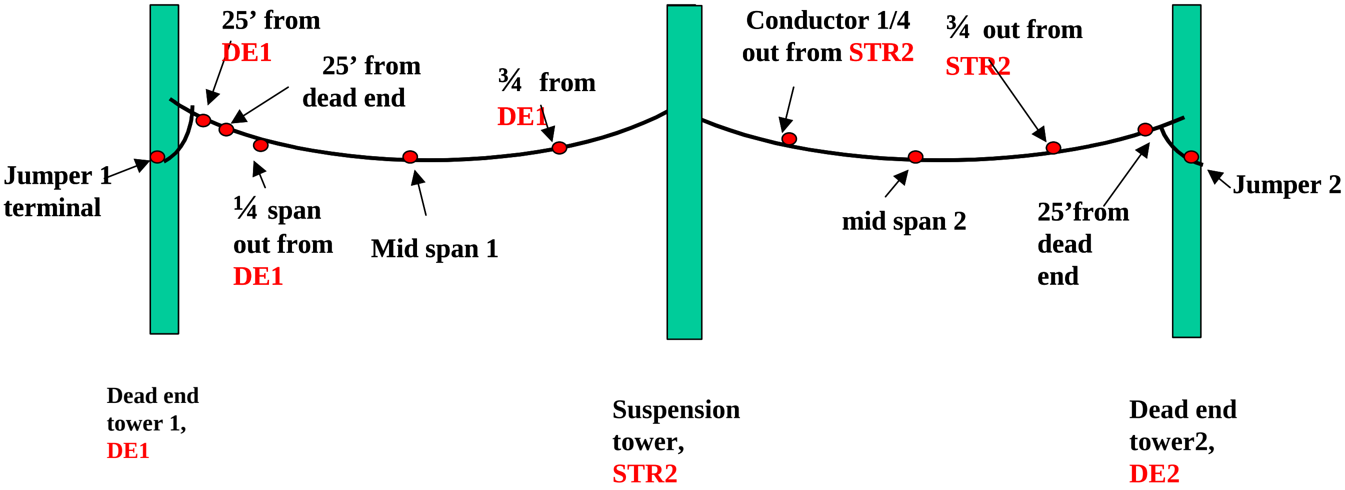


Figure 9- Schematics of thermocouples location along the test line spans from dead end tower DE1 to suspension tower, STR2 to dead end tower DE2.

The conductor was cycled from ambient to above 200^0 C using either constant current or constant temperature. It was given a short cycle from ambient to 300^0C on 11-28-05.

Figure 10 shows both a typical difference of about 5-10^{0}C between core and surface temperatures when the conductor temperature is above 200^{0}C.

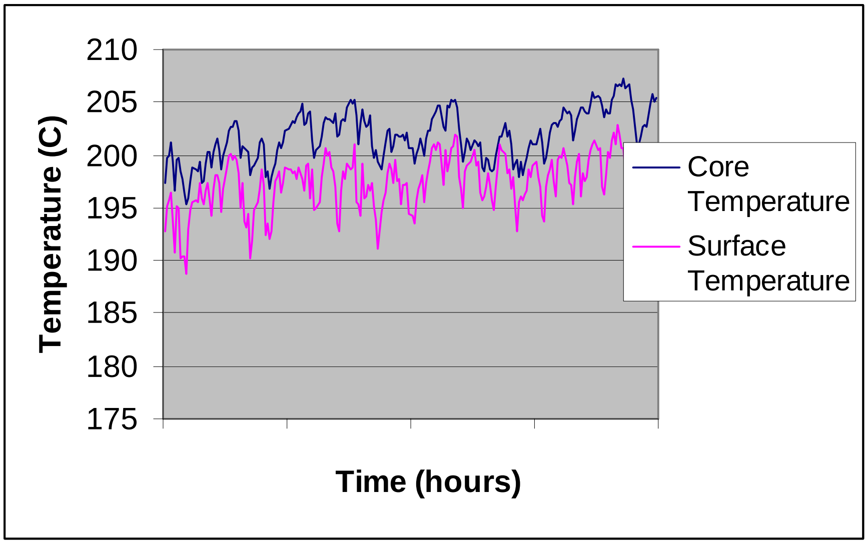


Figure 10 shows both surface and core temperature

November 2005 data was reduced to include only 0 fps wind speed and core temperature above 150^{0}C and plotted in figure 11. The data suggests that a larger temperature gradient occurs between core and surface at higher core temperatures.

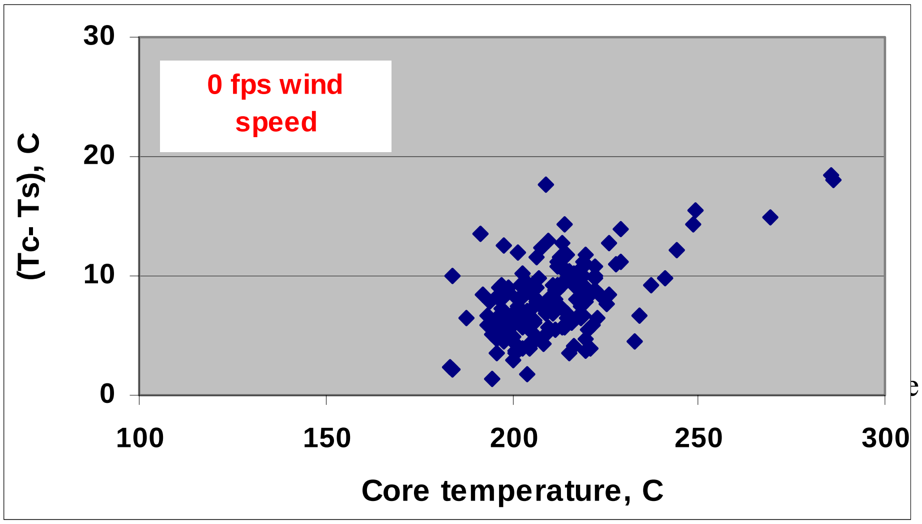


Figure 11 shows effect of conductor core temperature at 0 fps wind speeds on temperature gradient between core and surface

Data at wind speeds above zero was also examined and they show similar trend but higher difference, see figure 12.

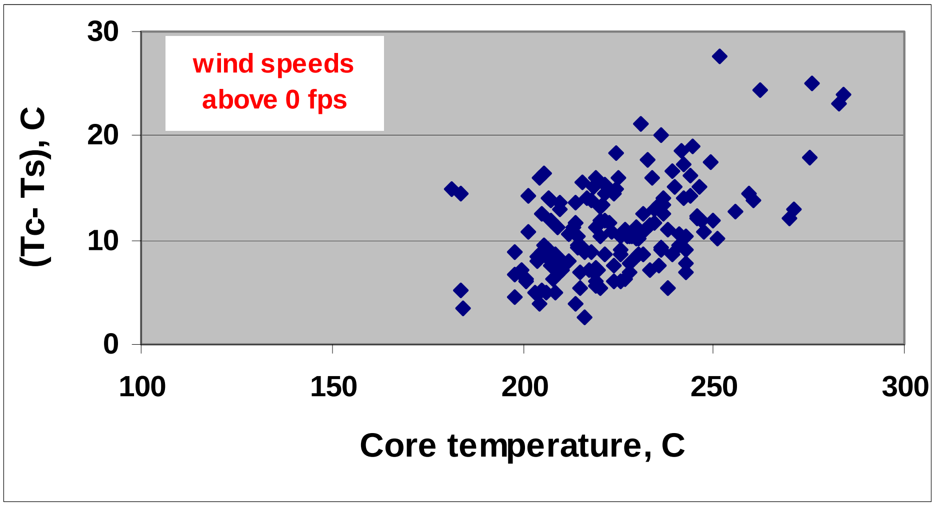


Figure 12- Temperature difference between conductor core and surface increases with increased core temperature at higher wind speeds

3-2 High temperature Cycle:

A high temperature cycle to 300^{0}C was conducted lasting about 40 minutes as shown in figure 13. No additional 300^{0}C cycles were performed because the thermocouple bond to the conductor deteriorated and some thermocouples were damaged.

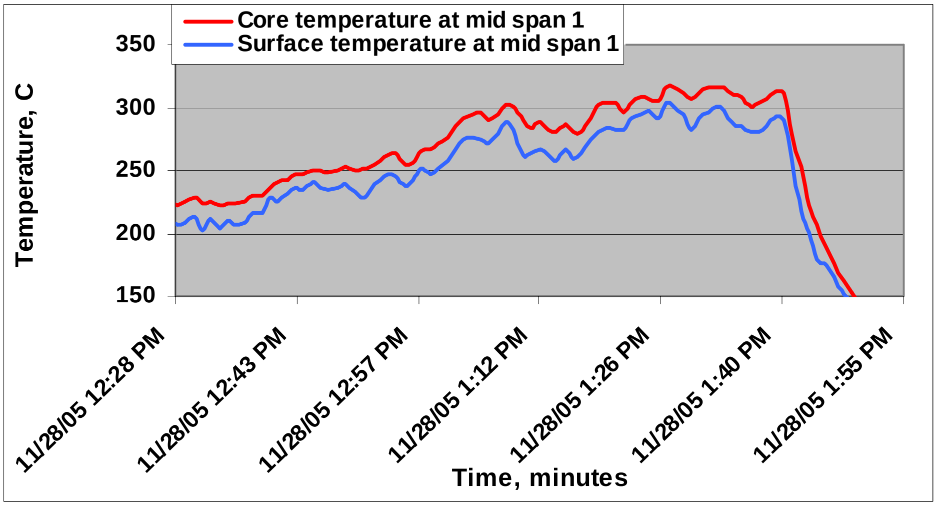


Figure 13- High temperature cycle, temperature difference between core and surface was about 15 to 200C at around 3000C core temperature

Table 3- Summary of thermal cycling of ACCR 795 at ORNL

Date	#Cycles Per day	Total # Cycles	Hours Per day	Total run hours	Nature of cycle	Maximum surface T, C	Average core T, C	Maximum Core T, C	Maximum current, A
6/16/2005	0	0	0	0	Conductor installed				
9/13/2005	1	1	1	1	Constant current, 1025A	127	122	130	1031
9/14/2005	1	2	13	14	Constant current,1200A	202	173	207	1226
9/15/2005	0	2	23	37	Constant current 1300A	196	177	199	1293
9/16/2005	0	2	20	57	Constant current1300A	211	187	216	1300
9/17/2005	0	2	1	58	Constant current, 1350A	207	205	211	1300
9/19/2005	1	3	16	74	Constant current 1300 A	208	183	214	1300
9/20/2005	0	3	24	98	Constant current 1300 A	213	192	221	1315
9/21/2005	0	3	24	122	Constant current, 1350A	246	208	252	1340
9/22/2005	0	3	24	146	Stepped current 1350A	226	200	230	1349
9/23/2005	0	3	4	150	Constant current, 1350A	205	203	208	1349
10/18/2005	1	4	2	152	Constant current, 1350A	156	156	160	1349
10/19/2005	1	5	15	167	Stepped current,1350A	199	156	201	1349
10/20/2005	0	5	24	191	Constant current, 1350A	222	210	228	1350
10/21/2005	1	6	24	215	Stepped current, 1350A	223	190	228	1350
10/22/2005	0	6	24	239	Constant current 1350 A	209	167	213	1350
10/23/2005	0	6	24	263	Tracking 175^{0}C all day	208	176	212	1350
10/24/2005	1	7	16	279	Tracking 190^{0}C, rain	253	199	253	1350
10/25/2005	0	7	24	303	Tracking 190^{0}C all day	247	195	252	1351
10/26/2005	0	7	24	327	190^{0}C then 100^{0}C (4PM to midnight)	220	202	226	1351
10/27/2005	0	7	24	351	Tracking 100^{0}C till noon, 125^{0}C after	135	136	138	1351
10/28/2005	0	7	24	375	1350 A, tracking 125^{0}C	162	141	170	1351
10/29/2005	0	7	24	399	1350 A, 100^{0}C target	131	120	139	1355
10/30/2005	0	7	24	423	1350 A till 9PM, then 1025A	110	100	113	1375
10/31/2005	0	7	24	447	Constant current, 1025A	113	97	117	1035
11/1/2005	0	7	24	471	Constant T around 1000 C	126	109	130	1606
11/2/2005	0	7	24	495	1400 A tracking 190^{0}C	256	210	267	1402
11/3/2005	1	8	23	518	1400 A tracking 200^{0}C	247	215	255	1378
11/4/2005	0	8	24	542	Tracking T around 200^0 C	233	208	242	1394
11/5/2005	0	8	24	566	T around 200^0 C, very windy	234	205	235	1485
11/6/2005	1	9	22	588	1400 A tracking 190^{0}C	247	217	255	1400
11/7/2005	0	9	24	612	1400 A, 190^{0}C	242	208	256	1407
11/8/2005	0	9	24	636	1401 A, 190^{0}C	217	204	224	1423
11/9/2005	0	9	24	660	1350A, 190^{0}C, very windy, rain	241	211	252	1437
11/10/2005	0	9	24	684	1350 A, 190^{0}C	237	204	243	1454
11/11/2005	0	9	20	704	Constant T around 200^0 C	257	220	268	1469
11/12/2005	0	9	24	728	Constant T around 200^0 C	243	217	254	1486
11/13/2005	0	9	24	752	1400A, 200^{0}C	244	219	251	1502
11/14/2005	0	9	24	776	Constant current, 1400A	224	215	229	1525
11/15/2005	0	9	24	800	T, 200^0 C	247	225	260	1543
11/16/2005	1	10	17	817	Current, 1550 A, storms, windy	251	221	259	1555
11/17/2005	0	10	24	841	Constant T, 200^{0}C, sunny, T rise	241	229	251	1566
11/18/2005	0	10	24	865	Constant T around 200^{0}C, sunny	275	223	293	1635
11/19/2005	0	10	24	889	Constant T around 200^0 C	243	221	257	1688
11/20/2005	0	10	8	897	Constant T around 200^0 C	217	214	225	1702
11/26/2005	1	11	8	905	Constant T, 200^0 C	216	202	223	1718
11/27/2005	0	11	24	929	Constant T, 200^0 C	249	225	263	1779
11/28/2005	1	12	21	950	T, 2000 C, rain 8-11AM, 3000 C spike	305	210	317	1843
11/29/2005	1	13	14	964	T around 200^0 C, Rain 9:30 AM	260	217	267	1897
11/30/2005	0	13	24	988	T around 200^0 C	261	227	272	2292

4- Measured and Predicted Line Tension and Sag:

The most commonly used method to compute both line tension and sag is the one developed by AFL and known as Sag 10; it is also referred to as the graphic method. It uses mechanical properties (Modulus, tensile strength, elongation and creep) measured in the laboratory. It assumes a Catenary shape for sagged conductor and takes into consideration environmental conditions (wind load and ice accumulation). A second method used in this report is called STESS, a model developed by Barrett and Associates, and is similar to the Sag 10 but varies in details where it allows to compute creep versus time. It uses a compressive stress values ranging from 0 to -2.45 Ksi to fit the data. The CAT-1 system measured tension on both the tree and road- sides of the line as a function of conductor temperature. Results are shown in figures 14 to 17. The STESS model shows good agreement at both high and low temperatures for the tree side when using -2.5 Ksi residual compressive stress. In the temperature range 60 to 120^{0}C agreement is not as good and may be due to processing variations in the residual stress of various Al strands. In general the model fits the high temperature data better, Figures 16 and 17.

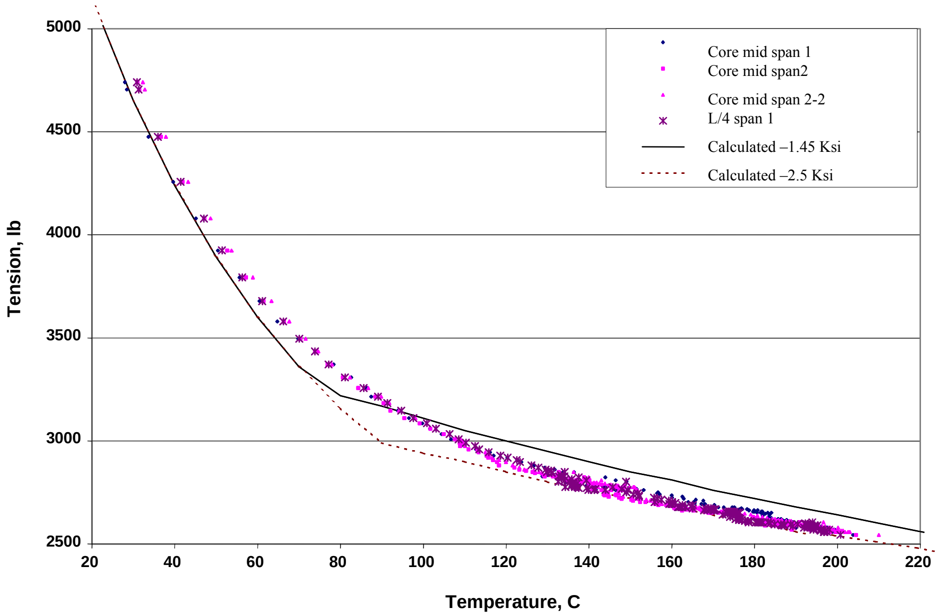


Figure 14. Tree side tension VS temperature on September 14, 2005. Model agrees with measured data at high temperature

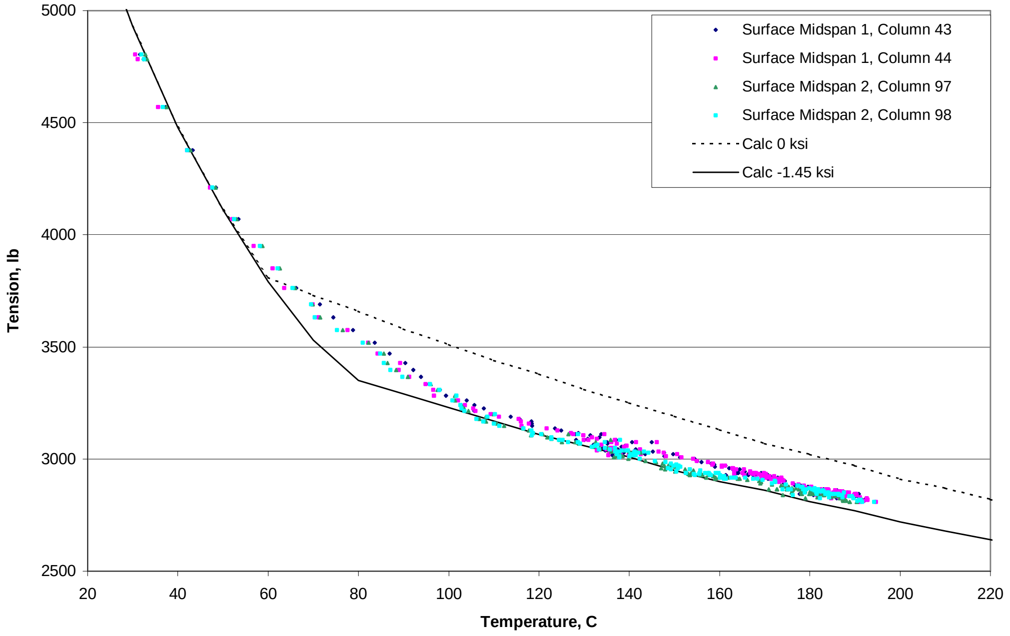


Figure 15- Road- side tension VS conductor surface temperature, September 14, 2005. Model fits data very well using a compressive stress of –1.45 Ksi particularly above 100^0 C

Similar results were obtained by analyzing the ORNL data for November 6, 2005.

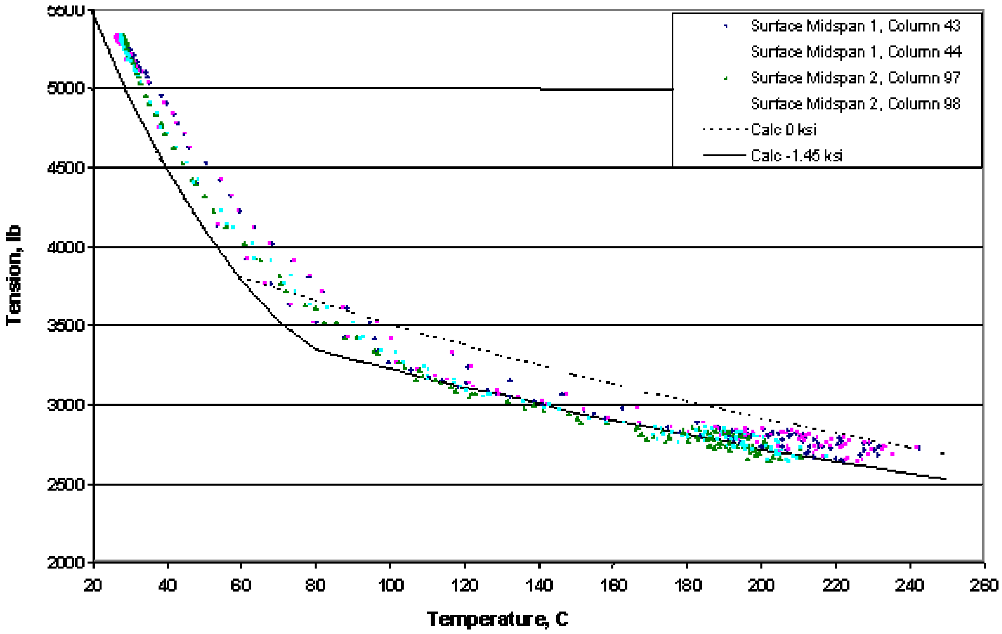


Figure 16- Road- side tension VS temperature, November 2005. Model agrees with measured data above 1000C using a compressive stress of –1.45 Ksi

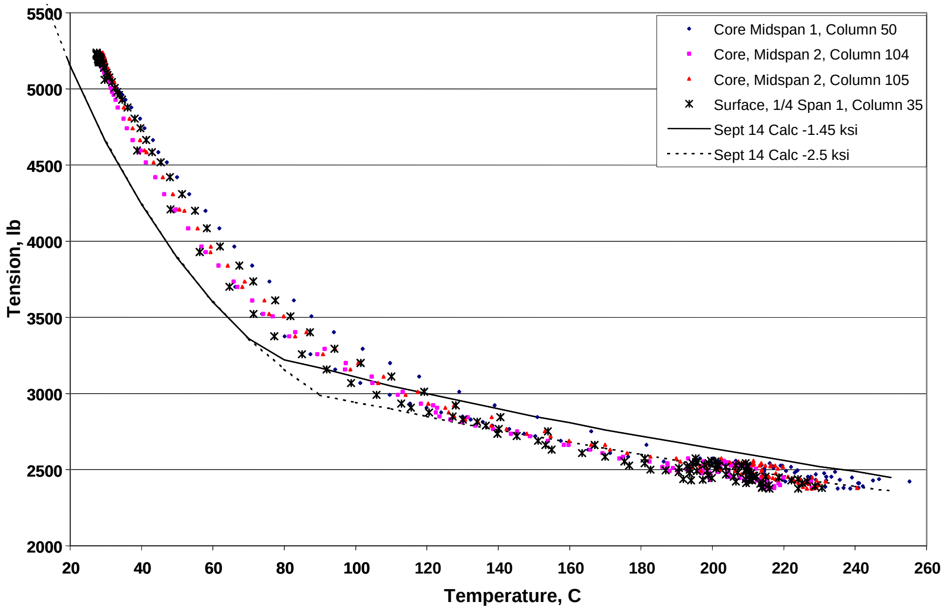


Figure 17. Tree side tension VS temperature, November 6, 2005. Model agrees with measured data at high temperature using Al compressive stress of –2.5 Ksi .

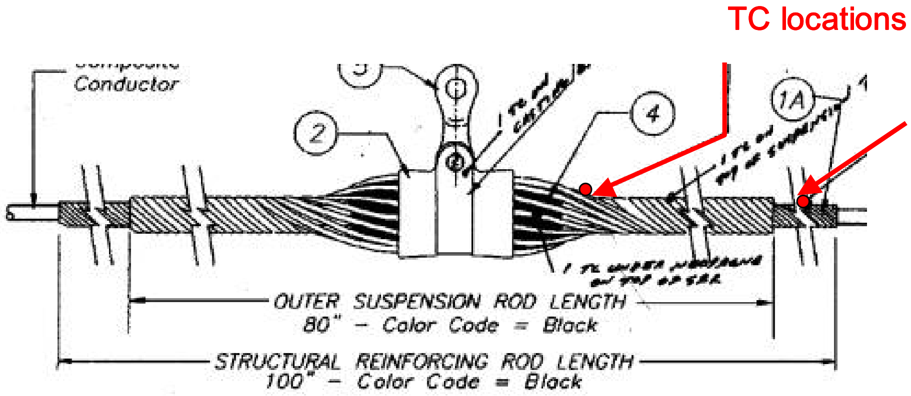
The STESS model agrees well with measured values at high temperature. Residual stress in Al may be traced back to the manufacturing process and it could be the cause of the absence of a well- defined knee- point for the conductor at the tree side. Laser measured conductor clearance above ground shows wide scatter; it could be due to changing wind conditions and because the measurement was done at a single location along the conductor surface.

5- Accessories Response at High Temperature:

Both Preformed Line Product and American Fujikura Ltd, AFL (Previously known as Alcoa Fujikura) accessories were used for installation of the line. They performed well and ran much cooler than the conductor during exposure to temperatures above 200^0 C.

5-1 PLP Accessories:

Temperature profiles of suspension, dead end and splice were measured. The thermocouples were mounted on both the outer and inner- stiffening rods as illustrated schematically in figure 19. The inner rods temperature was several degrees higher than that of the outer rods because of thermocouples proximity to the conductor strands and core- see figure 21.



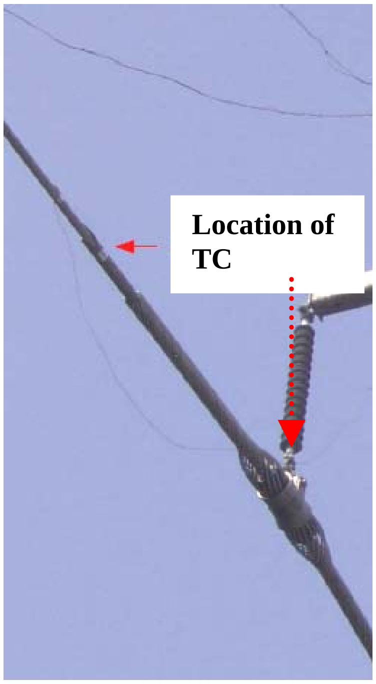
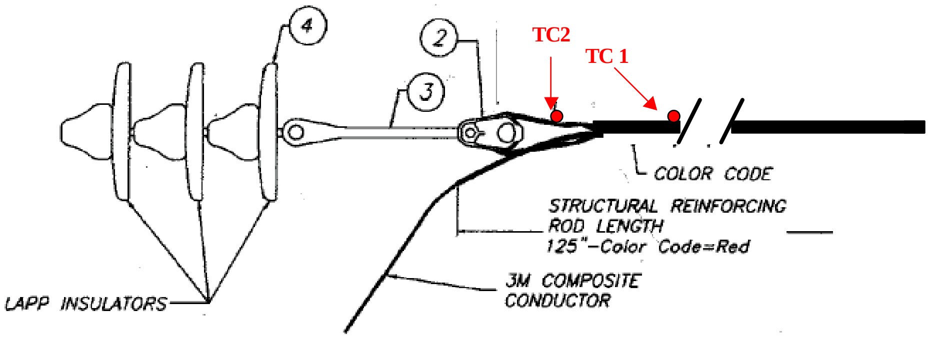
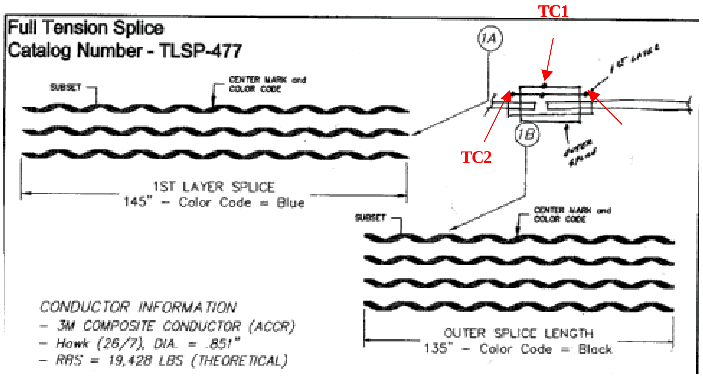


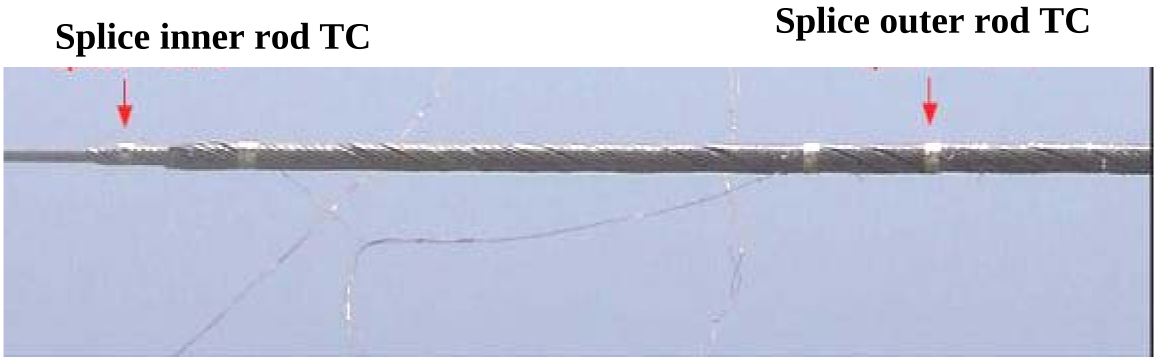
Figure 18 - Suspension System schematics showing thermocouples (TC) locations. The inner rod TC location is shown in the image very close to conductor



19- a PLP dead end Thermocouple, TC, Locations



19- b PLP Splice TC Locations



19-c actual location of thermocouples on the PLP splice

Figure 19- Schematics of thermocouples location on PLP THERMOLIGN^{TM} DEAD END and SPLICE and an image showing actual location of the two thermocouples.

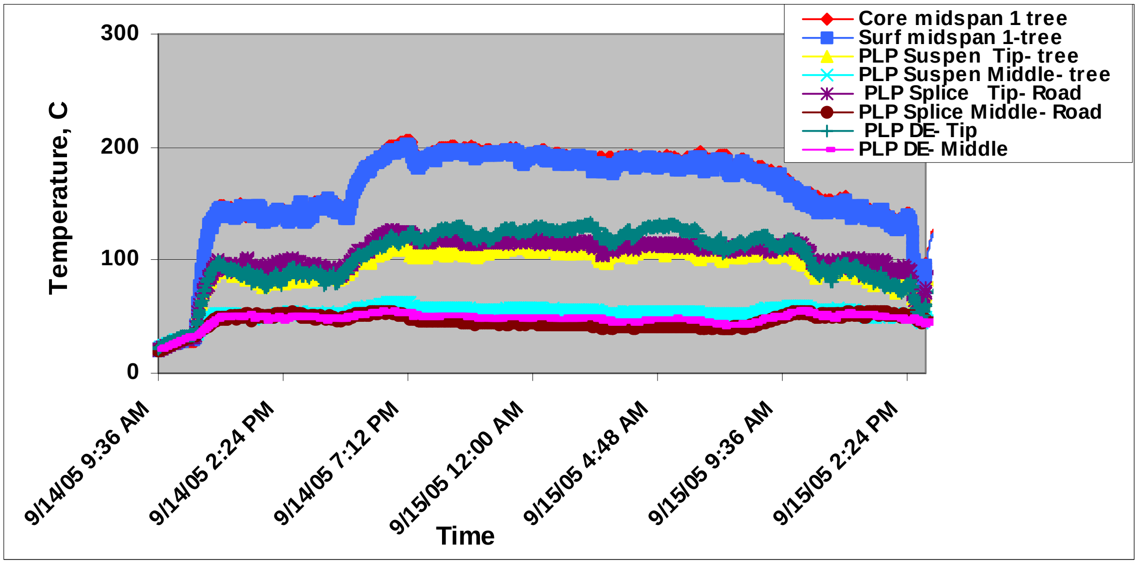
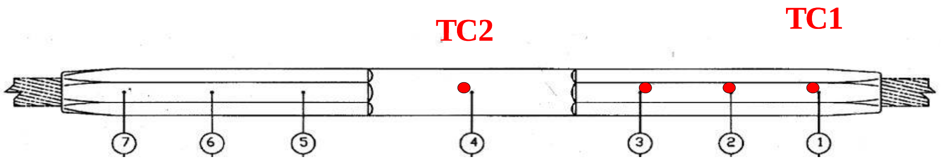


Figure 20- shows an example of PLP THERMOLIGN^{TM} SUSPENSION, SPLICE and DEAD END temperature profiles during conductor cycling at 150^0C and 200^0C. PLP accessories ran cool, below 120^0C at conductor temperature of 200^0C

5-2 Alcoa Accessories:

Both compression splice and dead ends temperatures were below 105^0 C during conductor exposure to temperatures above 200^0 C- see Figure 22. They show no problem during continued thermal cycling. Thermocouples were designated TC1 at the accessory mouth (hot- closer to conductor) and TC2 on the surface as illustrated schematically in figure 21.



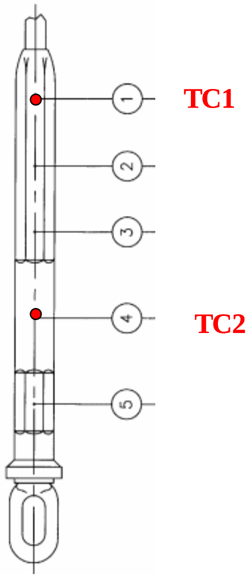


Figure 21- Thermocouples location on both the AFL compression dead end and splice.

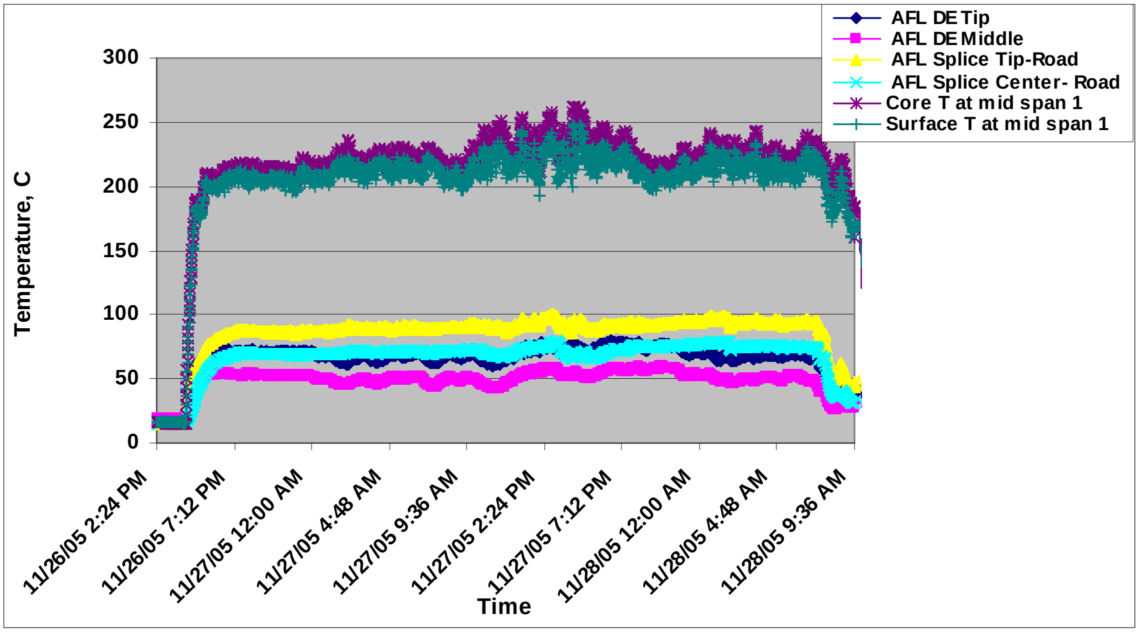


Figure 22- Alcoa compression splice and dead end temperature during one cycle; both ran very cool when conductor was at or above 200^0 C

All installed accessories ran cool when conductor was at or above 200^0C. Further Examination of conductor, accessories and their interfaces will be done after line is taken down to check for any changes as a result of thermal cycling.

6- Ampacity and Thermal Rating of Conductor:

6-1 Ampacity Prediction using IEEE Model

The IEEE Standard 738-1993-was used to predict conductor temperature during thermal cycling. Weather conditions for constant current and wind were used in the model; Figure 24 shows an example of steady state, high temperature cycle data used in the model. Figure 24 plots measured current VS predicted one (using both IEEE and CIGRE models) at conductor temperatures around 200^0 C; agreement is good. Conductor emissivity, ε =0.347, measured at ORNL in 2003, was used in the model calculations. ACCR 795. Conductor emissivity is not expected to change due to the low KV of the line (400 V). Conductor is rated at 1653 amps for continuous operation at 210^0 C and 1778 amps for emergency loading at 240^0 C. The data shows the conductor was sometimes exposed to temperatures higher than 240^0C and current above 2200 amps.

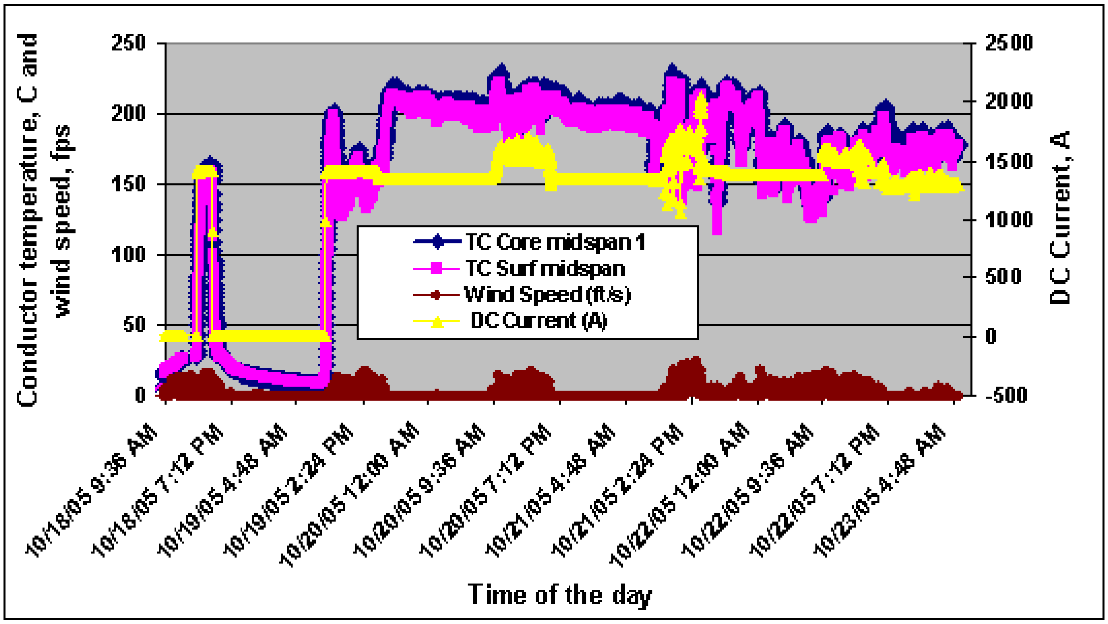


Figure 23 shows an example of constant current thermal cycles data used in the model prediction in October 2005

6-2 IEEE VS CIGRE' Ampacity Model:

The CIGRE' 1997 model was used to compute current to compare with the IEEE Std 736, both programs were provided by the Valley Group Rate kit software. There were small differences between the two models in agreement with literature data. Predicted current values agree well with measured current as plotted in figure 25..

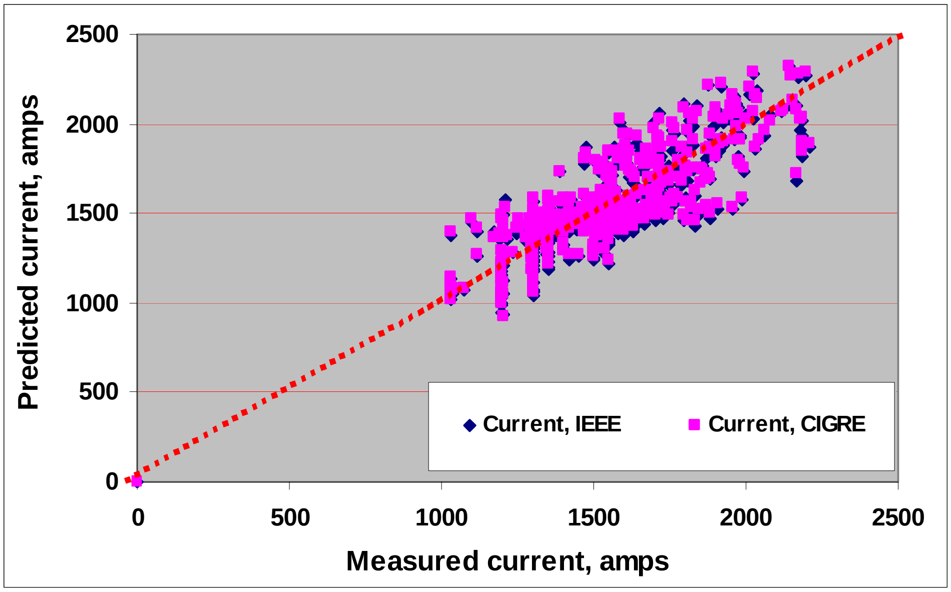


Figure 24- Comparison of both the IEEE and CIGRE predictive models with measured current data- Agreement is good

7- Summary:

ACCR 795 conductor was successfully installed and tested at ORNL. It was thermally cycled from ambient to over 200^0 C for several hundred hours, using a DC power supply. Measured temperature difference between conductor core and its surface was as low as 5^0C and as high as 20^0C degrees and depended on both wind speed and core temperatures at and above 200^0 C. Wind speeds above 0 fps produced larger temperature gradient from surface to core.

Data analysis shows that the measured conductor current agrees well with the IEEE thermal rating model predicted values. The conductor is rated at 1653 A current for continuous operation at 210^0 C and at 1778 A emergency current at 240^0C. The CIGRE' model agrees with the IEEE 736 model.

Conductor tension was stable during and after thermal cycling. Measured line tension versus temperature agrees well with values computed using the strain summation method, STESS.

Both PLP and AFL accessories ran cool, below 120^0 C at conductor's temperature exceeding 200^0 C. The conductor and accessories were exposed for up to 1000 hours at high temperature and show no visual damage. Conductor will be de-installed in early 2006 and shipped to NEETRAC for inspection and mechanical testing (residual strength). The results will be included in a follow up report.

8- Appendix

8-1 Conductor Specs

Designation		795-T16
Stranding		26/19
Diameter		
individual Core	in	0.082
individual Al	in	0.175
Core	in	0.41
Total Diameter	in	1.11
Area		
Al	in^2	0.624
Total Area	in^2	0.724
Weight	lbs/linear ft	0.896
Breaking Strength		
Core	lbs	18,556
Aluminum	lbs	12,828
Complete Cable	000's lbs	31,384
Final Modulus		
Core	msi	35.0
Aluminum	msi	8.6
Complete Cable	msi	12.3
Thermal Elongation		
Core	10^-6/C	6.3
Aluminum	10^-6/C	23.0
Complete Cable	10^-6/C	16.5
Heat Capacity		
Core	W-sec/ft-C	22
Aluminum	W-sec/ft-C	324
Resistance		
DC @ 20C	ohms/mile	0.1100
AC @ 25C	ohms/mile	0.1126
AC @ 50C	ohms/mile	0.1237
AC @ 75C	ohms/mile	0.1349
AC @ 100C	ohms/mile	0.1460
AC @ 210C	ohms/mile	0.1951

AC @ 240C	ohms/mile	0.2084
Geometric Mean Radius	ft	0.0375
Reactance (1 ft Spacing, 60hz)		
Inductive Xa	ohms/mile	0.399
Capacitive X'a	ohms/mile	0.0912

Appendix A.3

ACCR 1272 Kcmil Report

Composite Conductor Field Trial Summary Report: ORNL ACCR 1277 Kcmil

Installation date	August 9, 2004
Field trial location	Oak Ridge, Tennessee, USA

Line Characteristics

Organization	Oak Ridge National Laboratory
Point of Contact	John Stovall, ORNL
Installation date	August 9, 2004
Conductor Installed	ACCR 1272
Length of line	1,200 feet (356.7 meters)
Conductor diameter	0.858 inch, (21.8 mm)
Voltage	400 VDC
Ruling span length	600 feet, (183 meters)
Structure Type	Steel Poles
Instrumentation:	(1) Load cell (2) Current, voltage (3) Weather station (4) Sag (5) Thermocouples in conductor and accessories

Hardware

Suspension Hardware	Preformed Line Product, THERMOLIGN^{TM} SUSPENSION-TLS-0116-SE
Termination Hardware	AFL compression dead end, part# 1272M-54/19-ACCR, Drawing#B9085 AFL splice, part#1272M-54/19-ACCR, Drawing#B9095
Insulator type	Polymer
Dampers	Alcoa Dampers part# 1707-13
Terminals	AFL terminal connector, part#1272M-54/19-ACCR, Drawing# B9102 PLP THERMOLIGN^{TM} DEAD END, part# TLDE-1272-N

Results and Measurements

Full range of temperature tests from 30^{o}F – 412^{o}F (0^{o}C – 240^{o}C) with currents ranging from 0 to 1,800 amps

Sag-Temperature data from 0^{o}C – 240^{o}C
Line tension data from 0 to > 200C
Measured thermal rating

Table of Contents

Abstract:

Under DOE funding Agreement No. DE-FC02-02CH11111 Oak Ridge National Laboratory, ORNL, jointly with The Tennessee Valley Authority, TVA, successfully installed ACCR 1272 conductor on ORNL high temperature test line. The line is 1200 feet (365 meters) long, and the ruling span is 600 feet (130 meters).

ORNL subjected the line to severe thermal cycling and extended high temperature load using 400 V DC and current as high as 2700 amps. The conductor was thermally cycled between ambient and 200^0+ C for over 300 hours and over 100 hours operation continuously above 200^0 C under changing wind conditions.

The conductor tension and sag measured during the high temperature test trial agree with predictive models.

Predicted conductor current, using IEEE thermal rating ampacity method, agree well with measured values.

The accessories performed well during the high temperature cycling and ran at much cooler temperature than the conductor.

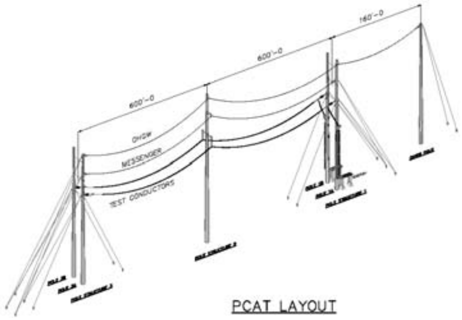
1- Background

ORNL has built a fully instrumented low-voltage test line to evaluate the high-temperature operation of ACCR conductors by simulating dozens of emergency cycles where the conductor temperature reaches operating temperature 210^0 C (400^oF) and higher under a range of ambient conditions.

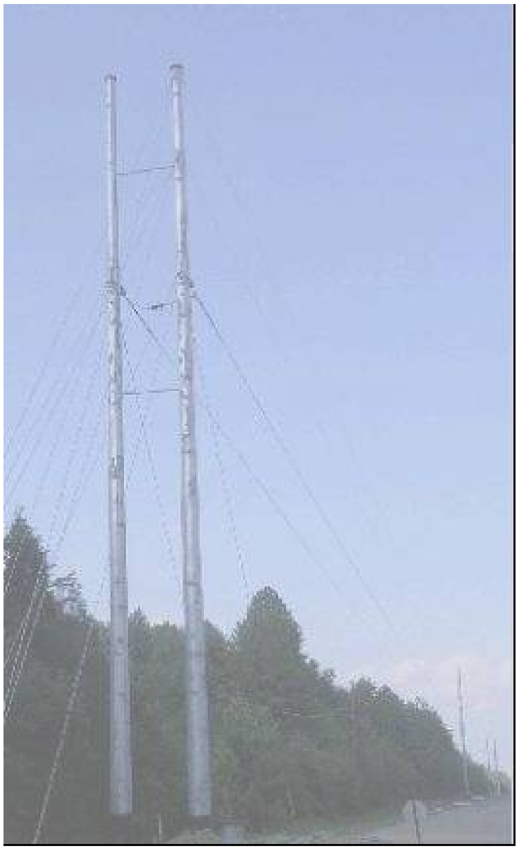
The ORNL test line instrumentation includes conductor tension measuring device, full weather station with anemometer, voltage, current, laser sensor device to measure sag, and temperature thermocouples in multiple locations in the conductor and in all accessories.

This report summarizes the 1272 ACCR conductor installation, testing and analysis at ORNL.

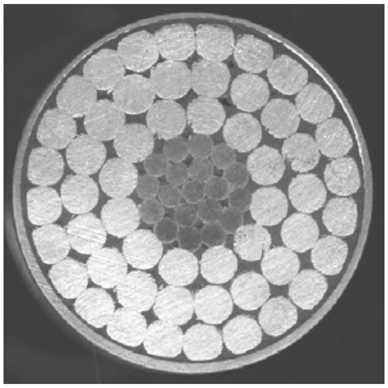
Arial view of the line



Layout



High temperature Line at ORNL



ACCR 1272

Figure 1- Conductor details and ORNL test line view

2- Installation and Conductor Stringing

2-1 Overview

A two span test line (from dead end to dead end) was constructed on the grounds of the Oak Ridge national Laboratory in Oak Ridge, TN, as a part of a Department of Energy program. Several sizes of ACCR composite conductors were installed and tested since then. ACCR 1272 is the latest of such installations. The installation procedures used is typical of that used when installing ACSR. Tables 2 and 3 show the typical hardware and procedures used during installations and the comparisons of each type of conductor.

2-2 Installation details:

The test line (Figure 1) consists of four 600 feet (183 meters) segments between a steel suspension pole and two guyed dual steel dead end poles. The test conductor forms a loop of two spans connected to a DC power supply located at one end of the line. Thermocouples were installed along the test conductor and on dead end, suspension and splice hardware to measure the temperature of these components during and after periods of high temperature operation.

Conductor was shipped to the installation site wound around wooden reels 84 " X36" X44 ". The installation of 1272 followed the IEEE 524 installation guideline for overhead transmission conductors. Grounded stringing blocks were used at all the dead end structures.

Particular care was given to the stringing operation. The combination of bending and tension if exceeds the core allowable strength could damage the conductor. Therefore stringing blocks and bull wheels were selected to keep the stringing loads way below conductor core strength. Table 2 specifies stringing blocks 28" diameter and bull wheels of 36" diameter to meet such criteria. Lined blocks were used with ACCR.

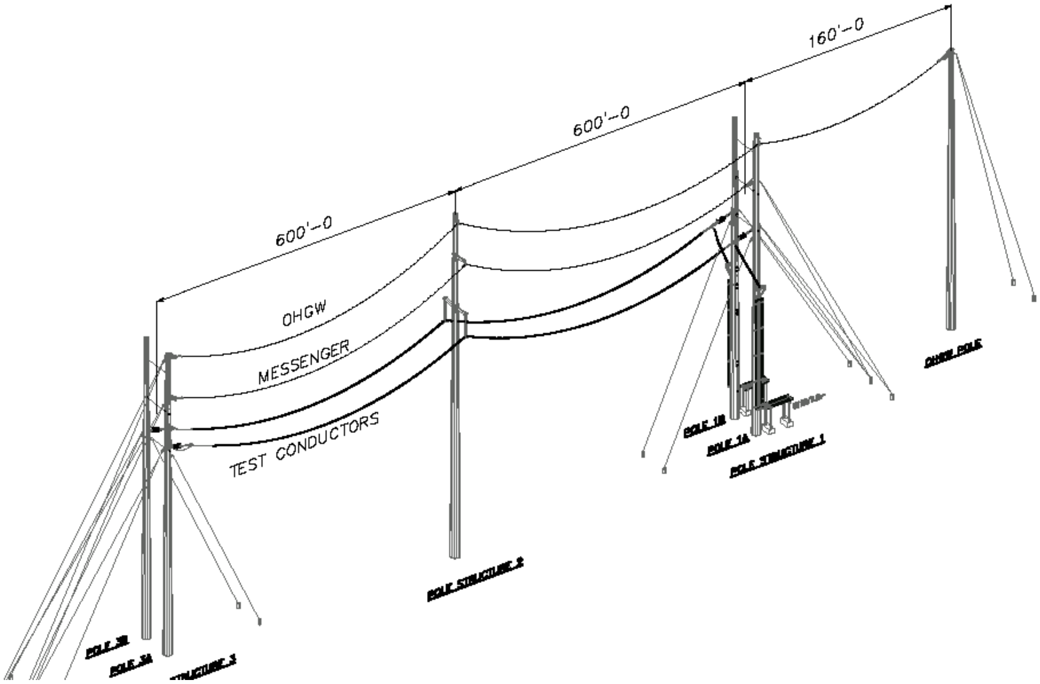


Figure 1 line Layout and PCAT –1 system

Figure 2- Sheave used in the installation

The sagging procedure of ACCR conductor is similar to that used to install ACSR; a dynometer was used to verify the final tension of the conductor.

Table 1- Installation Equipment and Procedure

Installation Equipment	ACSR	ACCR
Stringing Blocks	Yes	Yes (28”)
Bull Wheel	Yes	Yes (36”)
Drum Puller	Yes	Yes
Sock Splice	Yes	Yes
Conductor Grips	Any	DG-Grips
Cable Spools	Yes	Yes (40” Drum)
Cable Cutter	Yes	Yes
Reel Stands	Yes	Yes
Grounding Clamps	Yes	Yes
Running Ground	Yes	Yes

Installation Procedure	ACSR	ACCR
Cable Stringing	Tension / Slack	Tension
Sag Tensioning	Any	Line of sight, Dynometer
Dead Ending	Any	Use DG-Grip with chain hoists
Clipping	Any	Any

2-3- PCAT-1 Instrumentation:

A CAT-1 system from The Valley group was installed on one of the dead end structures to monitor the conductor tension and weather conditions (temperature, wind speed, and direction) at intervals of 10 minutes; see Figure 3. Two 10,000 pounds load cells were used for line tension. The CAT-1 system was equipped with anemometer to measure wind speed and direction. Data acquisition was done at 1minute interval for all channels

The CAT-1 main unit is in a NEMA-enclosed, solar powered, data acquisition and processing unit. Net Radiation Temperature, (NRT), was measured by the net radiation sensor, (NRS).

A- Load cell used to measure tension

B- CAT-1 System

3- C Net Radiation Sensor Measures
No Load Conductor Temperature

Figure 3- CAT system hardware

Net Radiation Temperature (NRT) was measured by the Net Radiation Sensor, Figure 3-C, which provides a simple method of combining ambient temperature with wind and solar effects (emissivity and conductor time constant).

2- 4 Conductor and Accessories Temperature Measurements:

A separate data acquisition system was used to collect the information from the thermocouples. Thermocouples were mounted at various locations along the span. The thermocouples were located on the conductor surface and several at the core. Additional thermocouples were installed on ALCOA compression dead ends, compression splice, Alcoa jumpers, PLP suspension, PLP splices and PLP dead ends.

2-5 Controls

The line was operated under either constant current and / or constant conductor temperature with thermal cycles lasting from one hour to several days.

Temperature data was acquired by thermocouples affixed directly to the outer surface and couple to the core. Multiple points along the length of the conductor were monitored this way. To accommodate the multiplicity of points along the conductor and withstand the accumulated voltage drop, many fiber-connected, isolated measurement nodes were used. A thermocouple measurement node was fabricated using a multiplexer (ICPCON I-7018) and a RS-485-to-fiber modem (B&B FOSTCDR). Up to eight thermocouples were monitored per node. The node required 120 VAC power and was connected through a duplex fiber optic network. The multiplexer, fiber modem, and a power supply were housed in an enclosure. The following images and those under accessories section show typical examples of the installation details

Figure 4- Installation of PLP THERMOLIGNTM DEAD ENDS next to stringing chain

The power supply used has a dual rating of 400 Vdc and 5000 amps or 600 Vdc and 3750 amps. The input voltage to the power supply is 4160 V, 3-phase. A dry-type ABB transformer was used to step down the voltage from a 13.8 KV distribution line.

2-6 Accessories:

Two types of accessories were installed; a compression type made by Alcoa (now named American Fujikura Limited, AFL) and formed wire type made by Preformed Line Products. The following specific parts were used:

- Four ALCOA compression dead ends; part # 1272-54/19-ACCR, Drawing # B9119, Dead ends consist of both direct core gripping parts and conductor gripping sleeve,
- One ALCOA full tension splice part# 1272M-54/19-ACCR, Drawing# B9095-D, it has the same design as the dead end for both direct core gripping and conductor.
- Six Alcoa terminal connectors; part# 1272M-54/19-ACCR, Drawing# B9102; those are all Aluminum sleeve parts
- Four Alcoa Stockbridge dampers; part# 1707-13
- Two PLP THERMOLIGN™, DEAD ENDS, part#TLDE-1272-N (includes extension link and Thimble- Clevis),
- PLP THERMOLIGN™ SPLICE part # TLSP-1272
- Two THERMOLIGN™ PLP SUSPENSIONS with Socket eye, part # TLS- 0116-SE

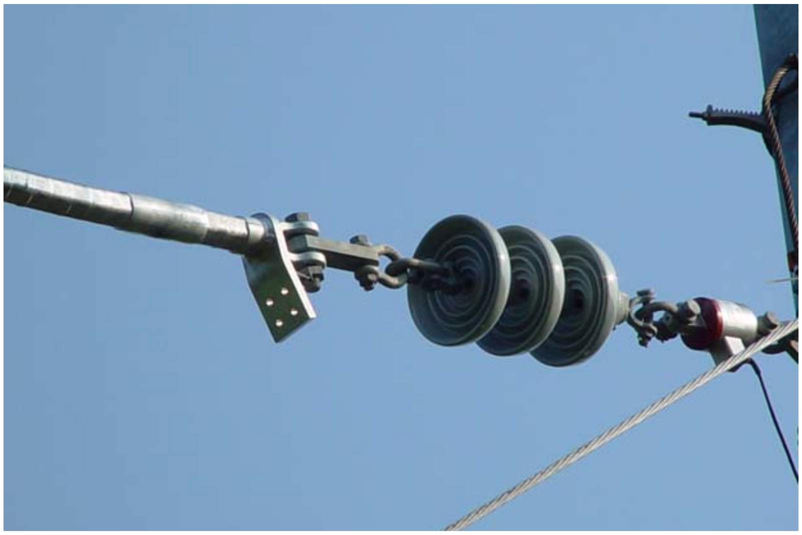


Figure 5- Installed Alcoa compression dead end next to insulator and dead end tower

Figure 6- Compression of jumper connector

3- Thermal Cycles and High Temperature Exposure:

3-1 Thermal cycles details:

The 1272 Conductor was thermally cycled starting in October 2004, between ambient temperature and 200^0+ C under wide range of weather and load conditions. A single cycle was carried out between ambient and 300^0 C and both conductor surface and core temperatures were recorded. Table 2 lists a summary of thermal cycles completed as of 4/6/2005

Table 2- Summary of Thermal cycling of conductor up to April 6, 2005

Date	#Cycles Per day	Total # Cycles	Hours Per day	Total Run Hours	Nature of cycle	Maximum Temperature, C	Maximum Current, amps
8/13/2004	1	1	9	9	Hi-Temp Run	220	2243
8/14/2004	0	1	21	30	Hi-Temp Run	221	2488
8/16/2004	1	2	8.5	38.5	Hi-Temp Run	222	2399
8/17/2004	0	2	24	62.5	Hi-Temp Run	228	2204
8/18/2004	0	2	24	86.5	Hi-Temp Run	224	2284
8/19/2004	0	2	24	110.5	Hi-Temp Run	223	2276
8/20/2004	1	3	5.5	116	Hi-Temp Run, Knee-point curve	217	2398
8/27/2004	7	10	7	123	Thermal/Mechanical Cycling	221	2500
8/28/2004	3	13	3	126	Thermal/Mechanical Cycling	217	2399
8/30/2004	1	14	1	127	Thermal/Mechanical Cycling	206	2400
8/31/2004	5	19	6	133	Thermal/Mechanical Cycling	213	2500
9/1/2004	8	27	8	141	Thermal/Mechanical Cycling	217	2500
9/2/2004	6	33	6	147	Thermal/Mechanical Cycling, rain	211	2499
9/3/2004	2	35	2	149	Thermal/Mechanical Cycling	205	2400
9/9/2004	6	41	6	155	Thermal/Mechanical Cycling	215	2400
9/10/2004	8	49	8	163	Thermal/Mechanical Cycling	222	2501
9/11/2004	8	57	8	171	Thermal/Mechanical Cycling	221	2500
9/12/2004	8	65	8	179	Thermal/Mechanical Cycling	218	2500
9/20/2004	5	70	5	184	Thermal/Mechanical Cycling	218	2501
9/21/2004	8	78	8	192	Thermal/Mechanical Cycling	221	2600
9/22/2004	8	86	8	200	Thermal/Mechanical Cycling	223	2600
9/23/2004	8	94	8	208	Thermal/Mechanical Cycling	221	2598
9/24/2004	6	100	6	214	Thermal/Mechanical Cycling	218	2599
11/9/2004	1	101	0	214	Checkout run, 1800 amps	143	2102
2/24/2005	1	102	7	221	7.5 hours @ 2000 amps	185	2003
3/18/2005	5	107	5	226	Thermal/Mechanical Cycling	222	2501
3/19/2005	8	115	8	234	Thermal/Mechanical Cycling	237	2721
3/20/2005	8	123	8	242	Thermal/Mechanical Cycling	233	2601
3/21/2005	8	131	8	250	Thermal/Mechanical Cycling	231	2600
3/22/2005	6	137	6	256	Thermal/Mechanical Cycling	198	2700
3/23/2005	5	142	5	261	Thermal/Mechanical Cycling	207	2703
3/24/2005	8	150	8	269	Thermal/Mechanical Cycling	200	2599
3/25/2005	8	158	8	277	Thermal/Mechanical Cycling	208	2500
3/26/2005	8	166	8	285	Thermal/Mechanical Cycling	211	2500
3/27/2005	4	170	4	289	Thermal/Mechanical Cycling	205	2601
3/29/2005	5	175	5	294	Thermal/Mechanical Cycling	201	2599
3/30/2005	8	183	8	302	Thermal/Mechanical Cycling	209	2699
4/4/2005	5	188	5	307	Thermal/Mechanical Cycling	203	2600
4/5/2005	8	196	8	315	Thermal/Mechanical Cycling	211	2602
4/6/2005	6	202	6	321	Thermal/Mechanical Cycling	206	2728
5/17/2005	1	203	13	334	Constant current	264	2002
5/18/2005		203	24	358	Constant current	216	1852
5/19/2005		203	11	369	Constant current	96	1231
5/26/2005	1	204	13	382	Constant current	165	1663
5/27/2005		204	17	399	Constant current	177	1777
6/7/2005	1	205	11	410	300C for 1 hour - 6:30 to 7:30 am	347	2275
6/8/2005	1	206	12	422	Constant temperature tests	143	1566

Figures 7 shows location of thermocouples for temperature recording along the entire conductor spans. Figures 8 to 10 show examples of the thermal cycling carried out on the conductor in the field; some cycles were of a constant temperature long duration, others were of a constant current and some cycles were very short. It should be noted that the used current sometimes exceeded the conductor rated ampacity, no evidence of conductor or accessory degradation.

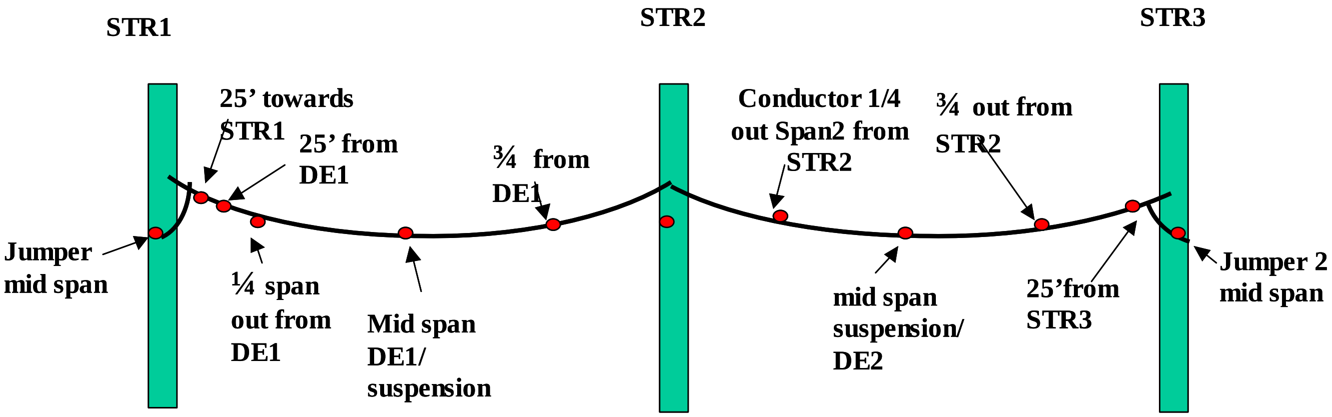


Figure 7- Schematics of thermocouples location along the test line spans; conductor surface temperature was measured at all locations while core temperature at only few.

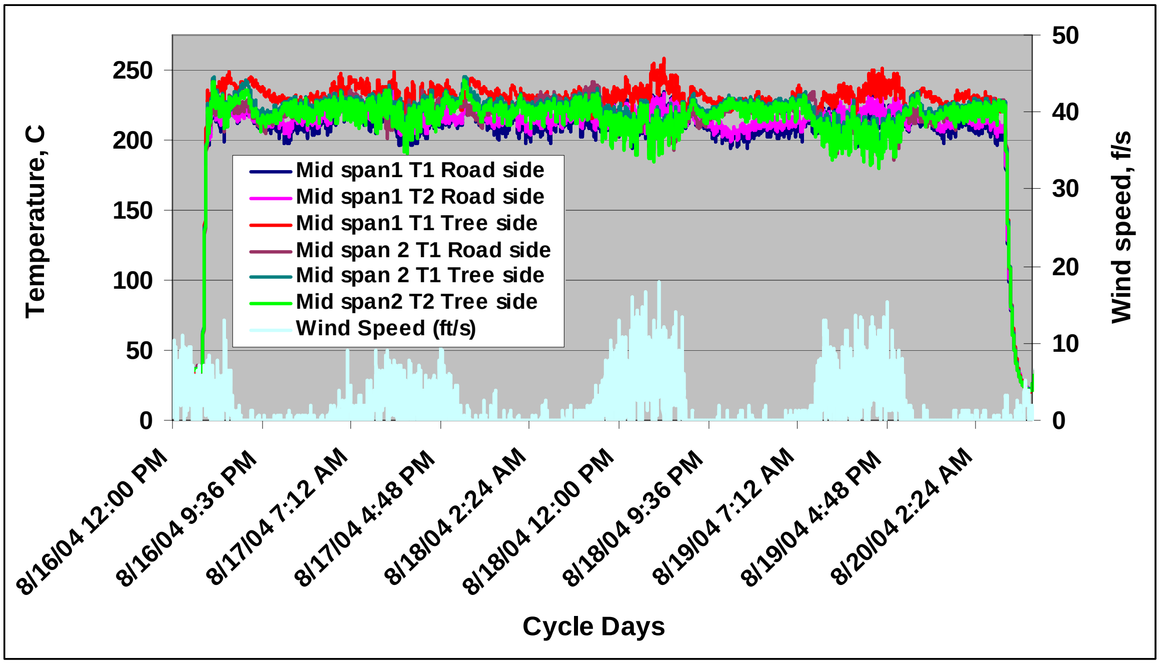


Figure 8 shows an example of about 85 hours single cycle above 200^0 C using DC current between 1900 to 2200 amps. Temperature was measured at two locations for each span for both the road and tree sides

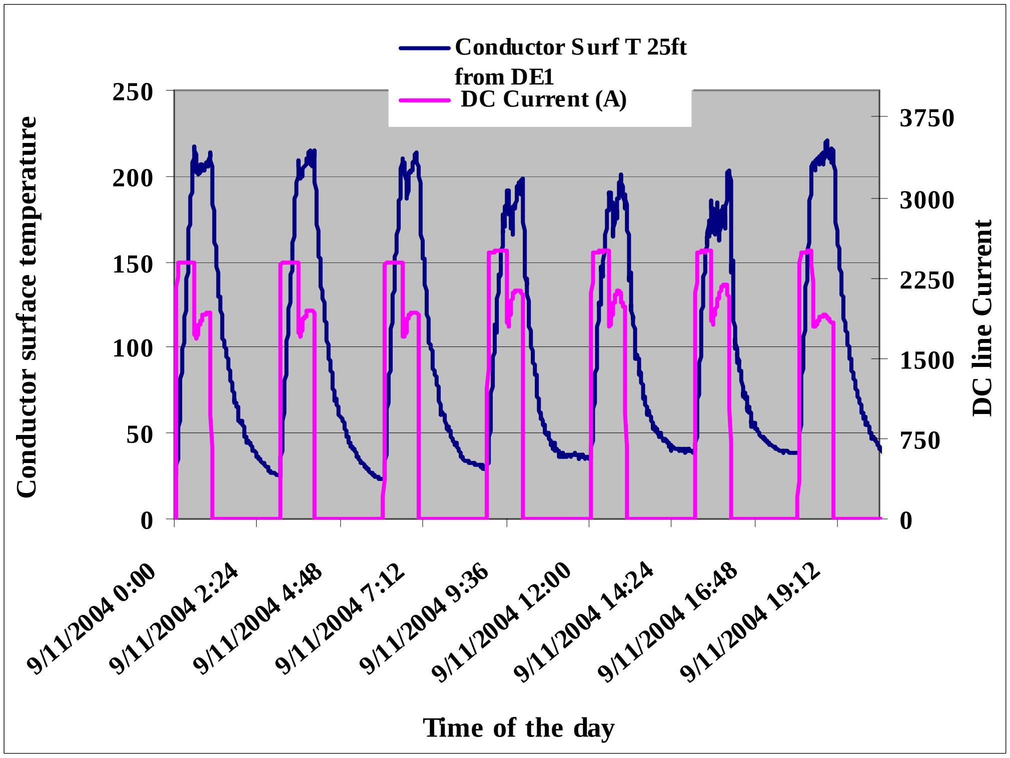


Figure 9 shows an example of short time multiple cycling of conductor in one day.

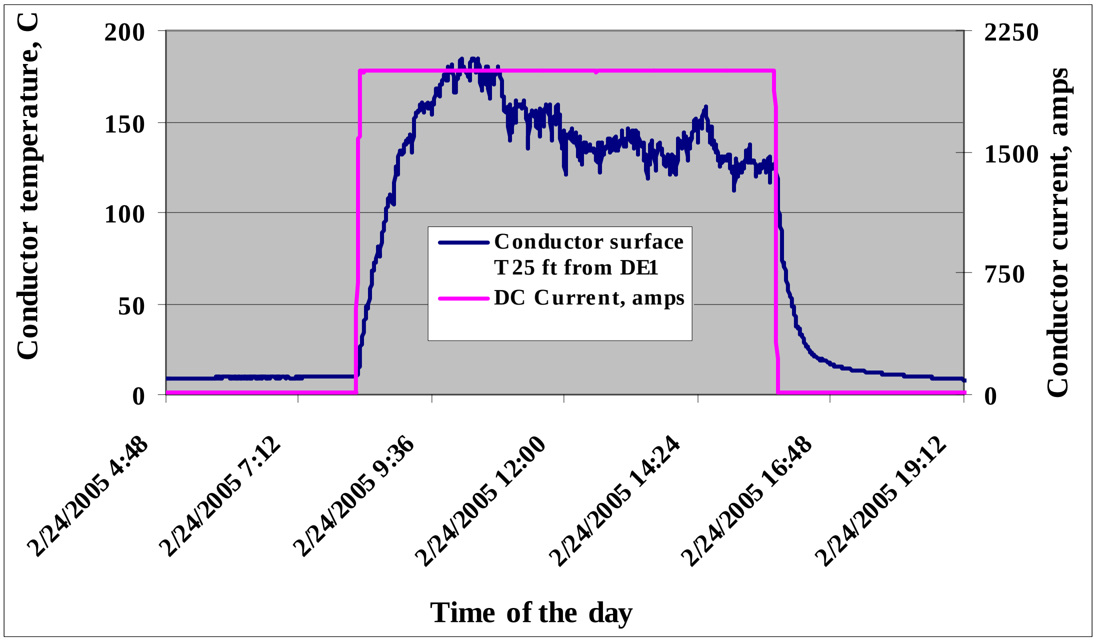


Figure 10 shows an example of a constant current cycle; conductor temperature is changing because of changing wind conditions.

3-2 Conductor Core VS Surface temperature:

Limited number of thermal cycles both at constant current and / or high temperature long time exposure was applied to ACCR 1272 while both core and surface temperatures were measured. Result shows that the core was only several degrees hotter than the conductor surface; see examples in figures 11 and 12. It also shows that the conductor was exposed to temperatures in excess of 230^0 C

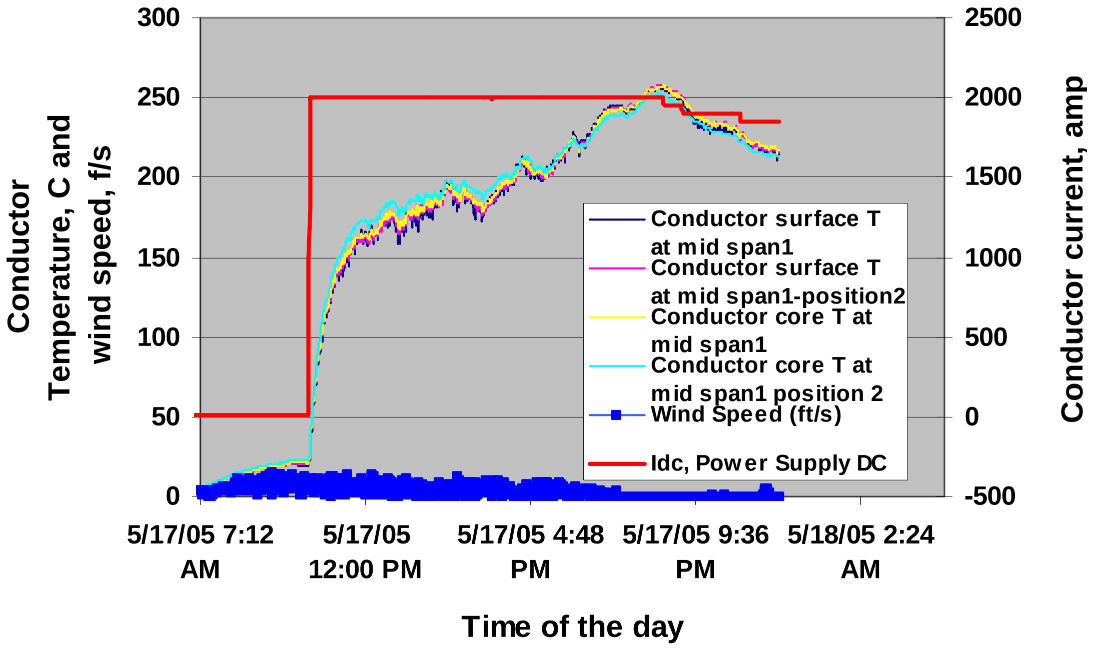


Figure 11. An example of a constant current thermal cycle of ACCR 1272 at ORNL on May 17, 2005

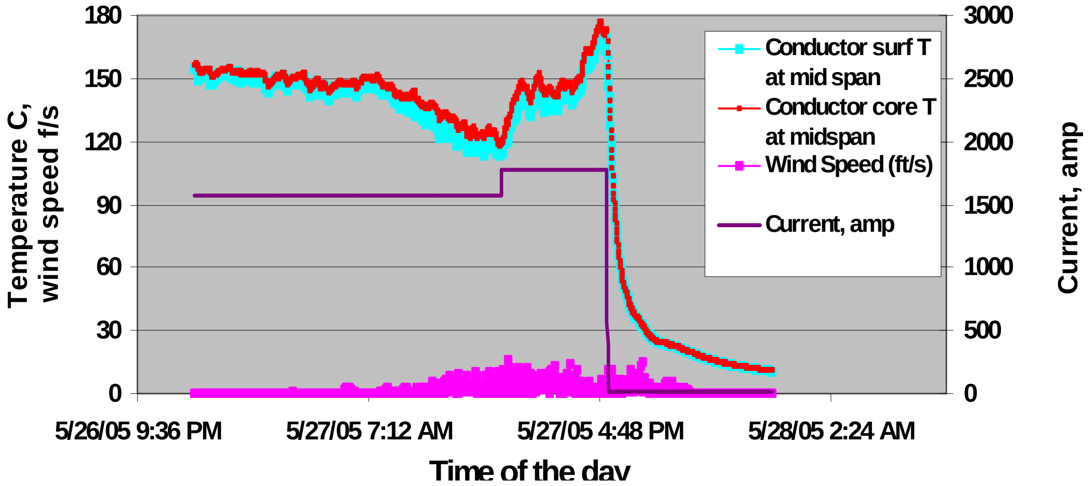


Figure 12. An example of a longer time thermal exposure with cycling around mid night of ACCR 1272 at ORNL on May 17, 2005

Wind speed appears to reduce both the Al strands surface temperature and core significantly as shown in the following figures 13 and 14.

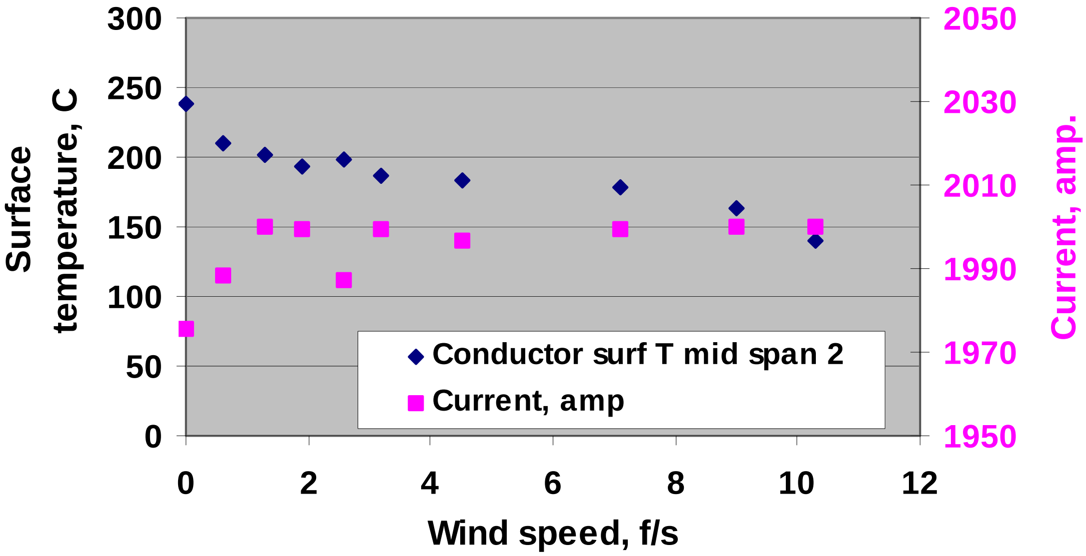


Figure 13. Effect of wind speed on conductor surface temperature at mid span when line is energized to about a current of 2000

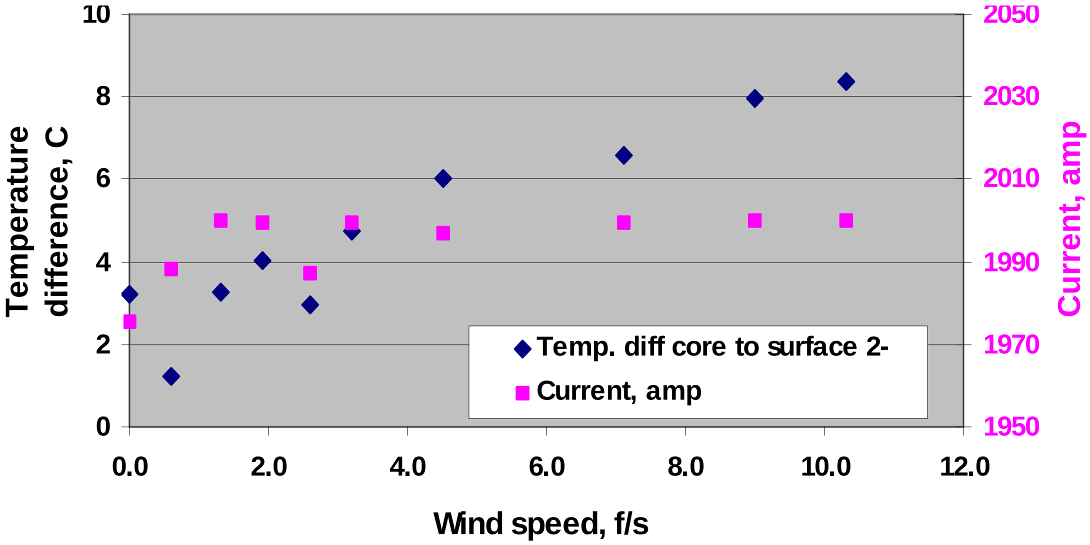


Figure 14. Temperature difference between core and surface at mid span VS wind speed at a constant current of 2000 amps at ORNL test line-

Conductor was exposed to a 300^0 C cycle for a short time and graph 15 shows the cycle details.

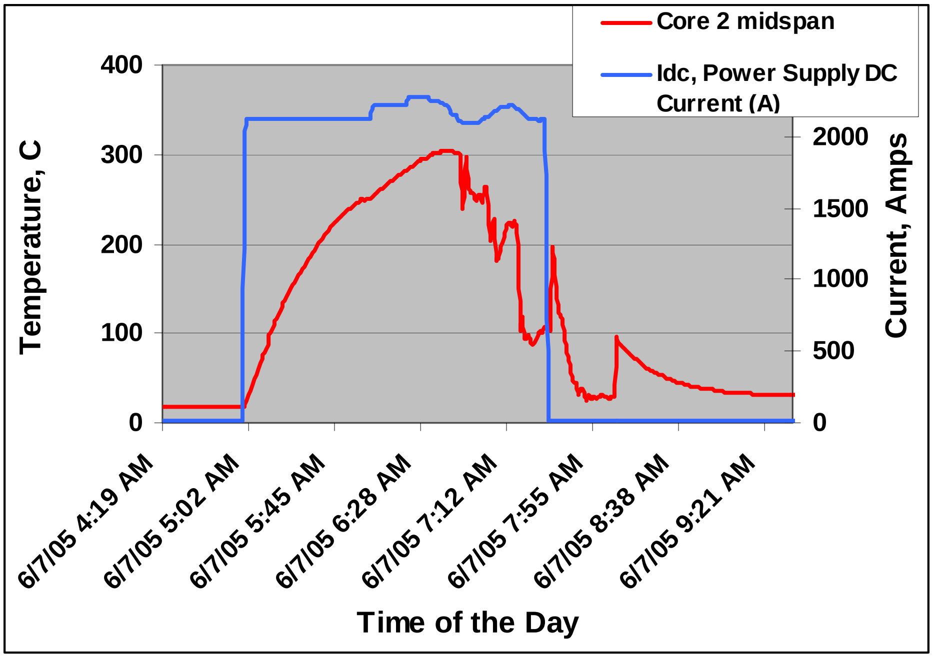


Figure 15 – Conductor core temperature and line DC current data measured during a 300^0 C cycle at the middle of span 1. The other thermocouples mounted on the conductor failed above 300^0 C.

Notice that the temperature gradient from surface to core was about several degrees, much lower than temperature gradients measured on smaller conductors (ACCR 477). Conductor was taken down in June 2005 and examined visually; it showed no damage and is being evaluated at NEETRAC Laboratories for effect of field testing.

4- Measured and Predicted Line Tension and Sag:

Sag was computed using, the Strain Summation Method (which accounts for the full loading history). The Strain Summation Method of Sag-Tension calculation takes into account creep as a function of time. The spans considered are two, tree side and roadside. Measured tension – temperature data is plotted in figure 16 for all tree side locations. The difference in tension is believed to be caused by differences in wind- speed, net radiation temperature, NRC (e.g. temperatures measured 25 ft from structure 3 in Span 2 were lower than temperatures at 3/4 Span 1) and line hysteresis. Figure 16 shows model predicted values using –1.45 Ksi compressive stress compared to measurement at ¾ span 1 and 25 feet away from STR3 on span 2; fit is good at high temperature. At lower temperatures the residual tension from line hysteresis raised the measured values above the computed ones. Calculated Curve is the same as that computed for the first heat cycle conducted on August 13- 14.

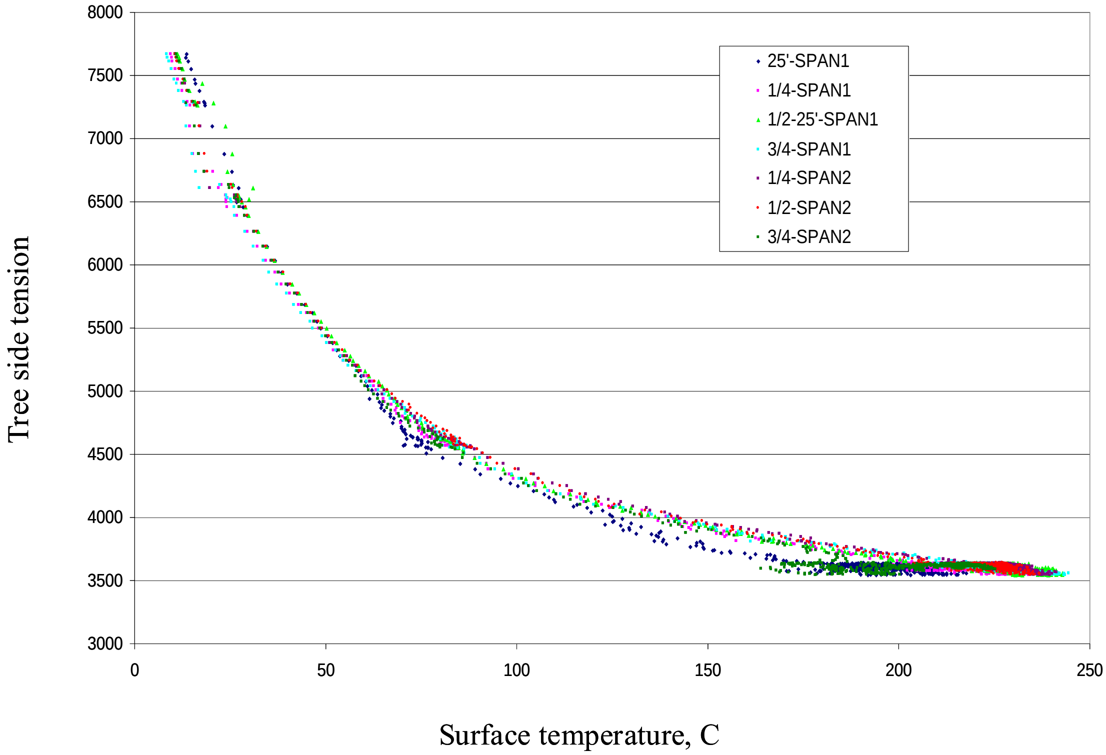


Figure 16- Measured line tension at various locations of spas 1 and 2 along the tree side VS conductor surface temperature.

Tensions (and sag) remained stable throughout 195 hours of heat cycling (81 cycles) up to nominally 220°C and sometimes up to 250°C.

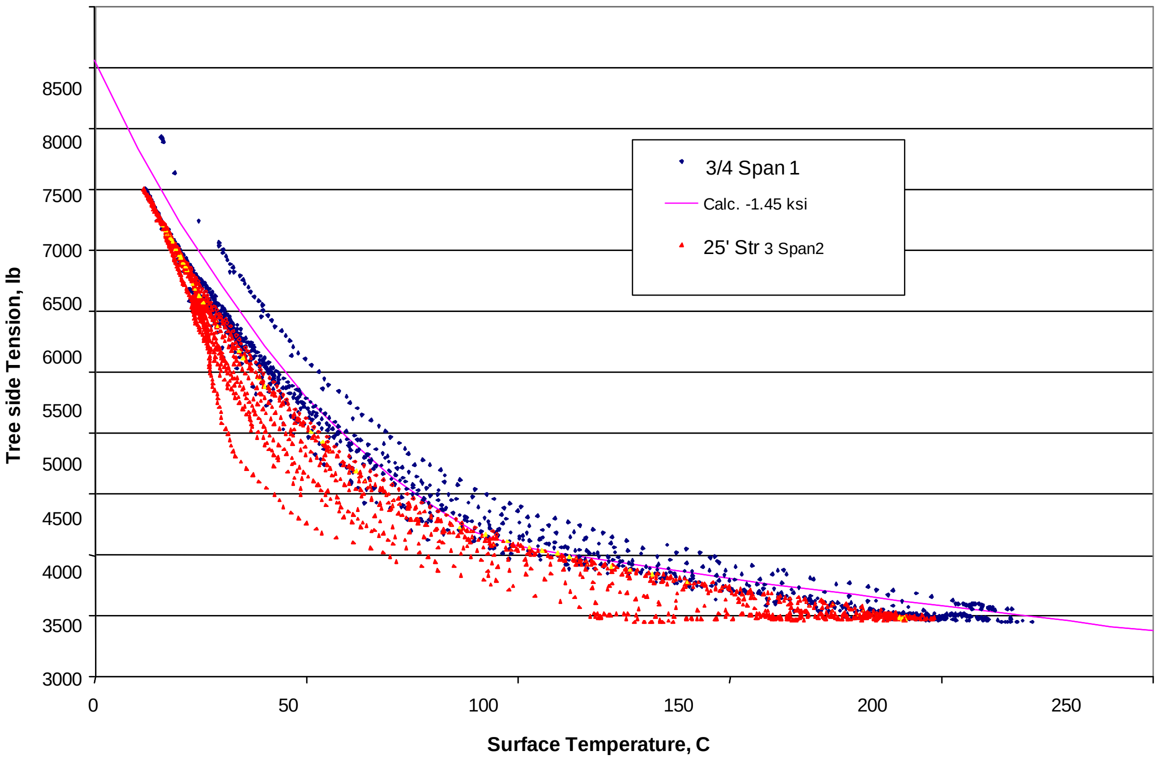


Figure 17- Field measured data acquired on September 21, 2004 for both spans 1,2 show good agreement with model using –1.45 Ksi compressive stress.

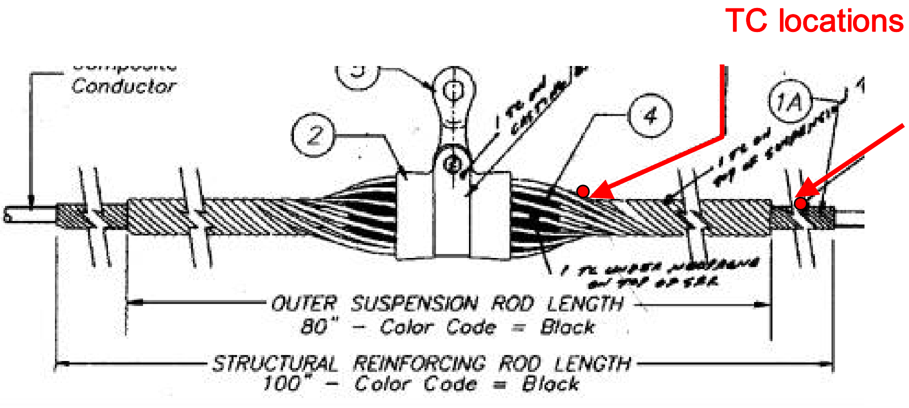
In conclusion the PCAT test line remained stable during the thermal cycle period analyzed here from August to September 2004. Model agrees well with measured values. Additional thermal cycling was carried out from October 2004 to June 2005.

5- Accessories Response at High Temperature:

Both Preformed Line Product and American Fujikura Ltd (Previously known as Alcoa Fujikura) accessories were used for installation of the line. They performed well, as expected, and ran much cooler than the conductor at temperatures above 200^0 C. Same was observed when they were tested in the laboratory at NEETRAC. The following Graphs 17 to 21 show examples of accessories temperature profile and location of thermocouples.

5-1 PLP Accessories:

Temperature profiles of suspension, dead end and splice were measured, figures 19.



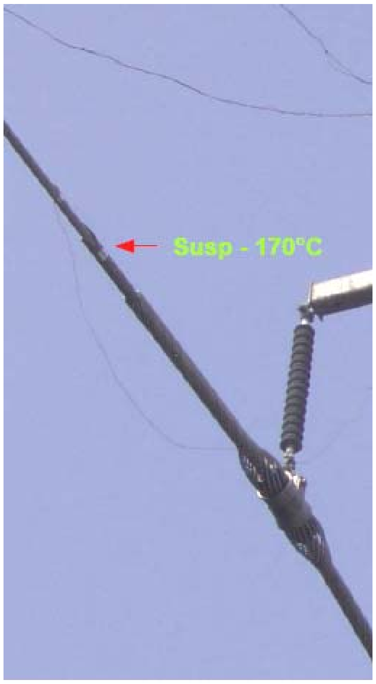


Figure 18 - Suspension System schematics showing thermocouples (TC) locations) , the inner rod TC location is shown in the image it is very close to conductor- the 170^0C is its temperature during a 300^0 C cycle

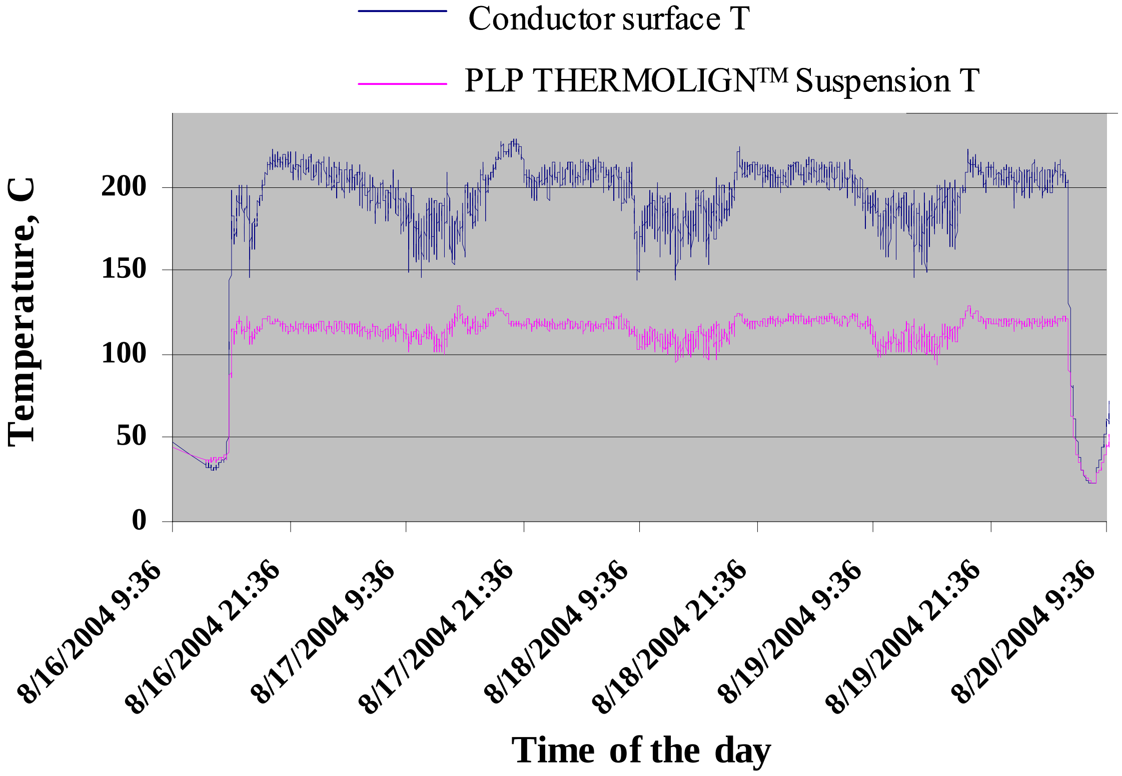
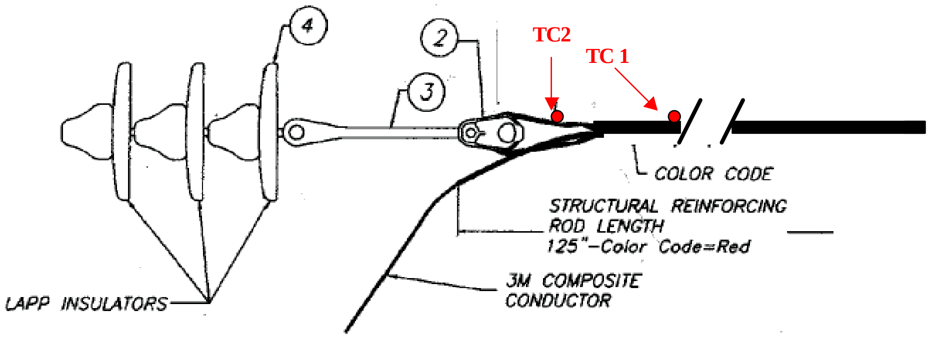
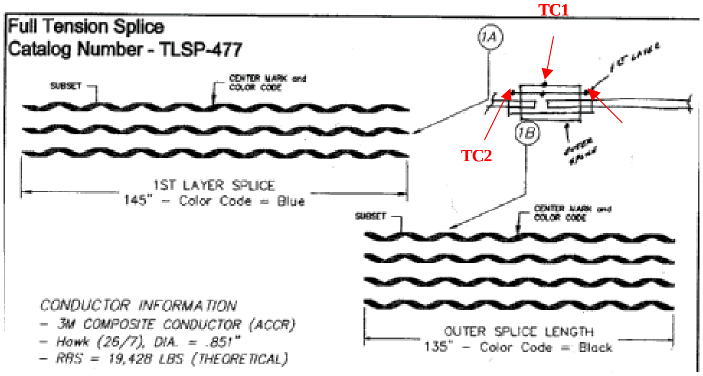


Figure 19 shows PLP THERMOLIGN^{TM} SUSPENSION System temperature measured on the surface of the inner rod during a long time high temperature cycle- other location TC was not active.





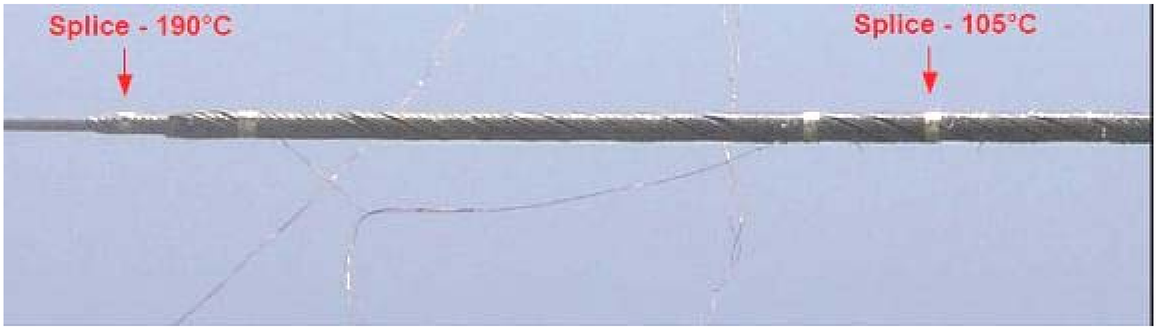


Figure 20- Schematics of thermocouples location on PLP THERMOLIGN^{TM} DEAD END and SPLICE. Image to the right shows location of the two thermocouples- temperatures of 190 and 105^0 C were the highest when conductor was cycled to 300^0 C.

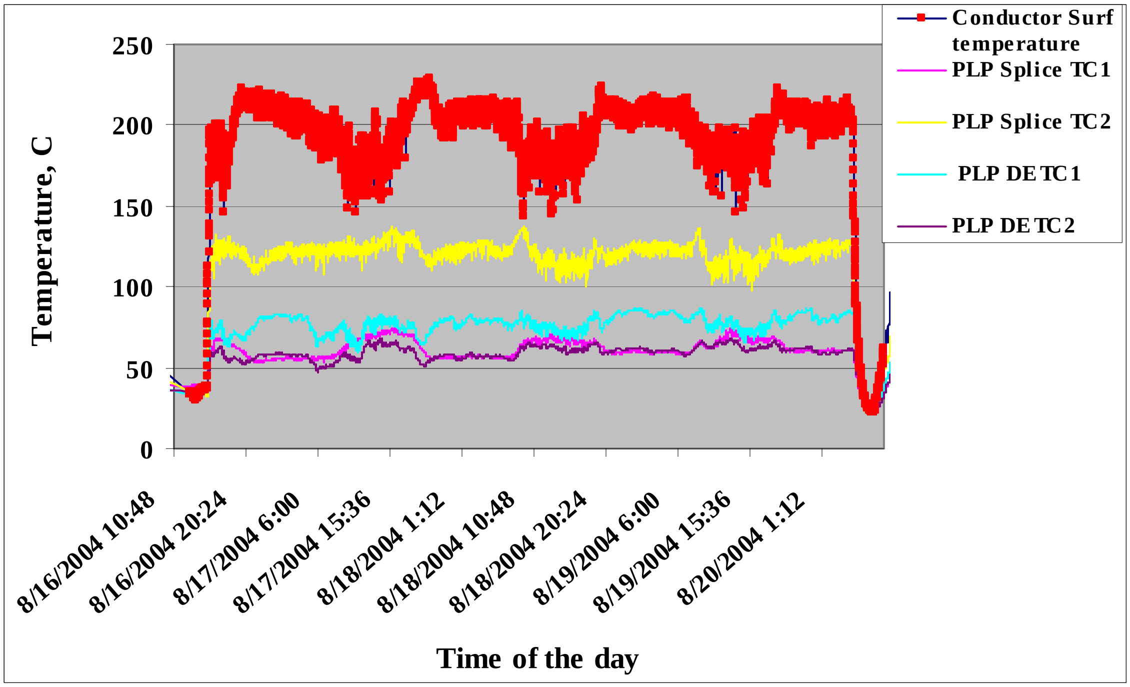


Figure 21- PLP THERMOLIGN^{TM} SPLICE and DEAD END ran cool, maximum temperature was below 130^0 C when conductor was cycled to 210^0 C

High temperature cycle:

The PLP accessories temperature profile was measured during a 300^0 C single cycle.- see figure 22:

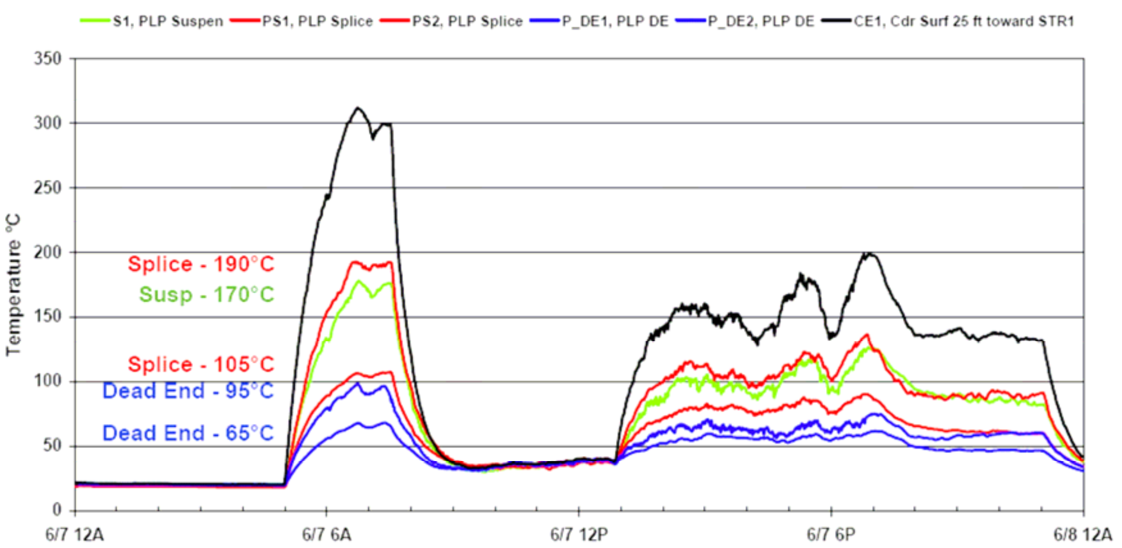


Figure 22- Temperature profile of PLP dead end, splice and suspension during 3000 C cycle of ACCR 1272 conductor. Some of the accessories temperature values was higher than 150^0 C because of the location of the thermocouples very close to the conductor- explained below

The splice temperature was 190^0 C and the suspension temperature was 170^0 C because thermocouples were placed on the inner rod first layer close to conductor. When the thermocouple was placed on the second rod layer mid way along the axial length of second layer of rods splice temperature dropped to 105^0 C. Dead end temperature was lower, 95^0 C (thermocouple placed on first layer of rod adjacent to second layer and 65^0 C (thermocouple placed on second layer of rods mid way along the axial length of the second layer of rods. The following images show location of thermocouples.

5-2 Alcoa Accessories:

Both compression splice and dead ends temperatures were below 105^0 C during conductor exposure to temperatures above 200^0 C- see Figure 22. They show no problem during continued thermal cycling since October 2004.

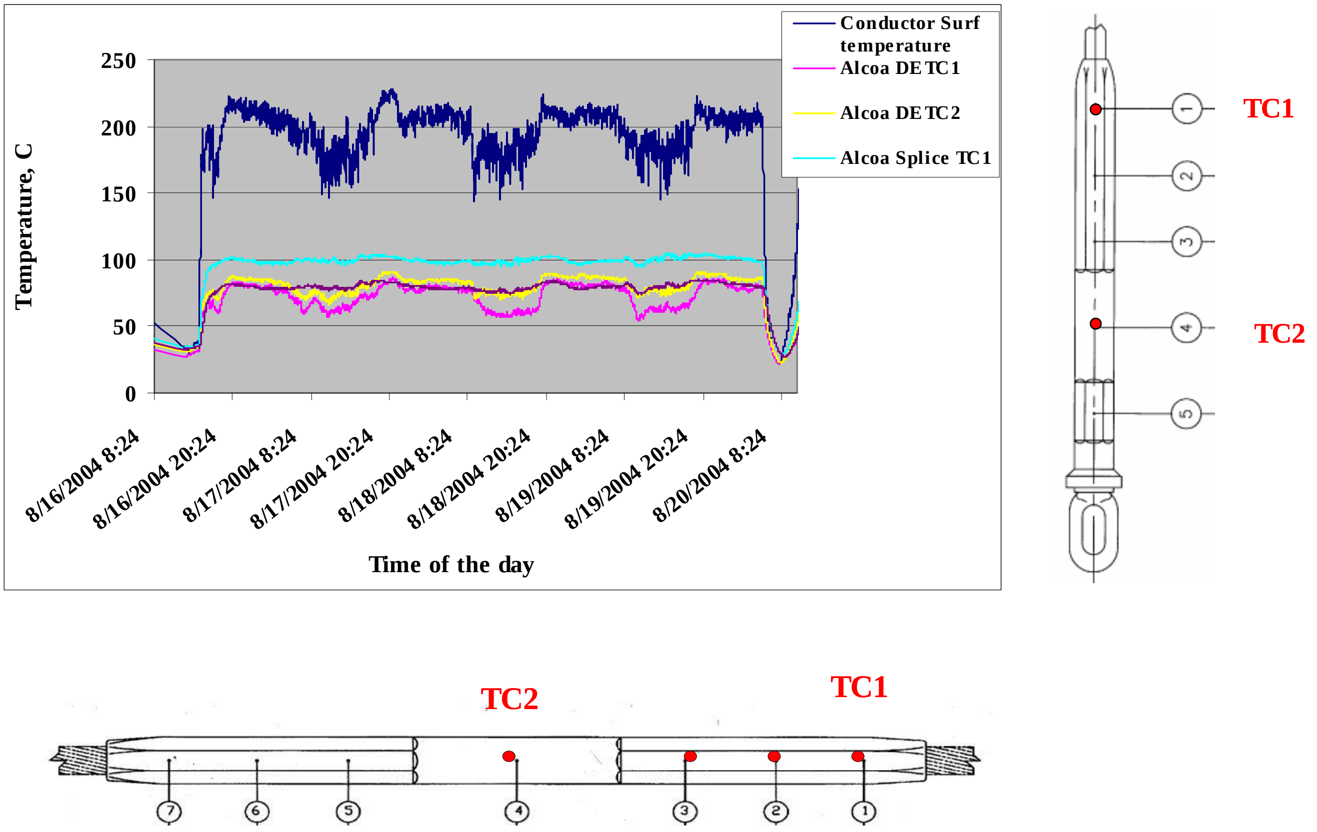


Figure 22- Alcoa compression splice and dead end temperature during one cycle; both ran very cool when conductor was at or above 200^0 C

High temperature cycle:

The Alcoa dead end and splice remained cool, below 1200 C when conductor was cycled to 300^0 C.

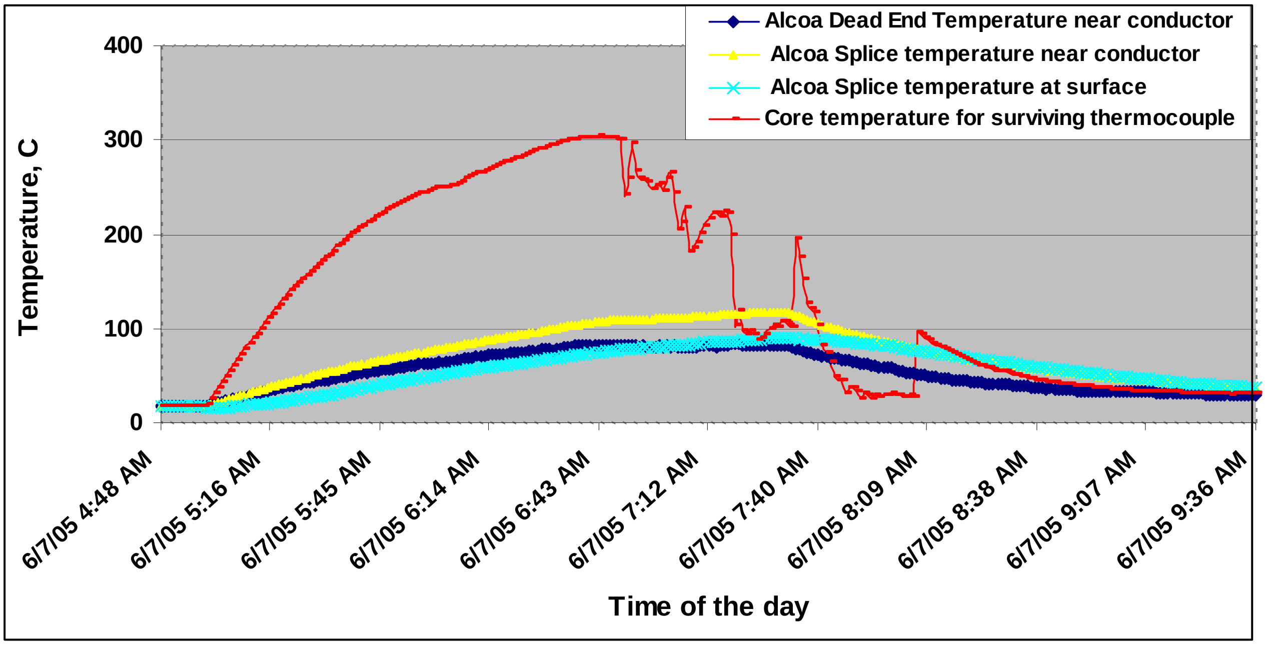


Figure 23- temperature profile of Alcoa dead end and splice during thermal cycling of the conductor to 300^0 C

All 1272 installed accessories behaved normally during thermal cycling of the conductor to above 200^0 C. Post thermal cycle conductor and accessories are being evaluated at NEETRAC.

6- Ampaciy and Thermal Rating of Conductor

6-1 Ampacity Prediction using IEEE Model:

The IEEE Standard 738-1993-was used to predict conductor temperature during cycling. The thermal cycle details are in Table 2. Weather conditions for constant current and wind were used in the model; Figure 24 shows an example of steady state, high temperature cycle data used in the model. Table 3 gives selective steady state data at each wind speed while Figure 25 plots measured current VS predicted one at conductor temperatures around 200^0 C; agreement is very good. Conductor emissivity, ε was measured at ORNL in 2003 and reported to be around 0.347 and used in the model.

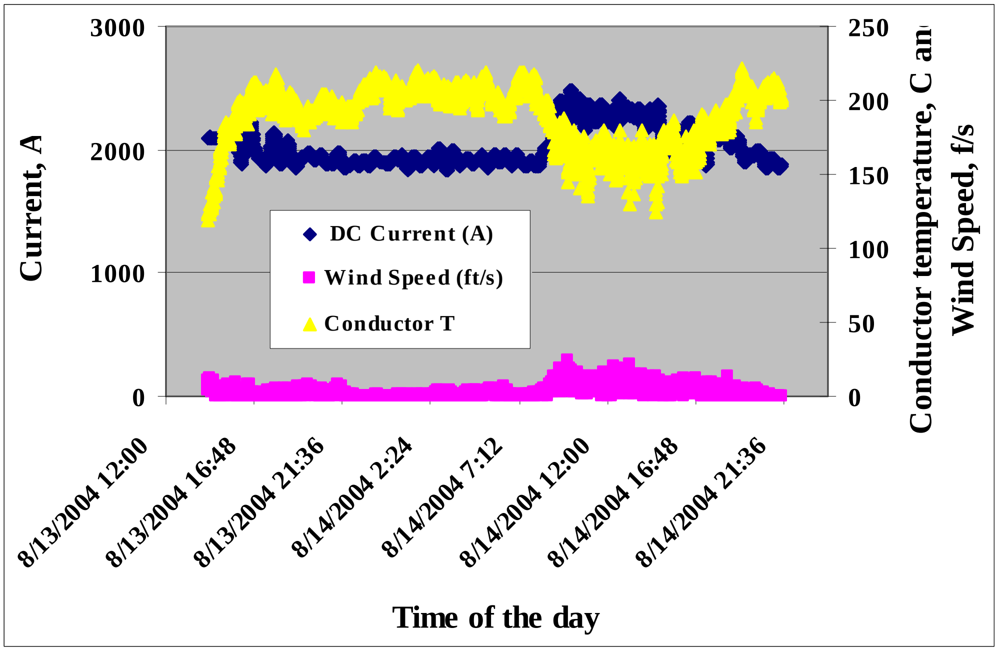


Figure 24- An example of high temperature steady state cycle conducted on ACCR 1272. Data from those cycles in August 2004 was used to predict current

Table 3 shows data for predicted VS measured current- IEEE Std. 738-1993 was used

Measured Current A	Ambient Temp. C	Wind Speed (ft/s)	Wind Angle degrees	Conductor Temp. C	Wind dirction degrees	Predicetd Current A		Measured Current A	Ambient Temp. C	Wind Speed (ft/s)	Wind Angle degrees	Conductor Temp. C	Wind dirction degrees	Predicetd Current A
0	23	0	10	23	0	0		1333	25	6	10	64	210	1141
545	20	1	13	23	53	213		1344	24	7	31	61	189	1376
698	20	0	30	26	10	309		1354	25	2	9	65	229	908
699	21	0	21	28	331	342		1364	25	6	29	68	249	1384
699	21	0	39	29	79	382		1376	25	3	4	68	224	938
699	21	0	57	31	97	405		1387	25	3	11	68	151	992
699	21	0	40	31	80	419		1396	25	5	15	69	235	1177
699	22	0	71	34	111	463		1408	25	2	5	71	215	965
700	20	0	18	27	328	327		1420	25	3	0	73	220	988
700	21	0	53	29	103	362		1429	25	9	13	70	207	1390
700	21	0	15	29	55	372		1439	25	11	14	70	206	1485
700	21	1	68	30	108	439		1448	25	6	9	72	211	1254
700	21	1	53	30	93	437		1459	25	7	14	67	206	1290
700	21	0	18	33	58	448		1471	25	5	27	71	193	1319
700	21	0	64	33	104	454		1480	25	6	36	66	176	1406
701	21	1	60	30	100	520		1489	25	8	12	70	208	1360
701	21	1	85	33	125	593		1499	25	5	12	73	208	1227
701	21	0	78	33	142	446		1510	25	10	0	74	220	1283
702	20	0	23	25	63	262		1520	25	13	2	72	218	1380
702	21	0	30	28	10	348		1530	25	8	14	72	206	1383
702	21	0	25	32	65	441		1540	25	5	38	75	182	1491
706	22	0	28	35	68	485		1550	25	15	13	73	207	1646
711	22	0	67	35	153	493		1561	25	13	7	75	213	1500
719	22	1	38	35	182	592		1572	25	14	7	73	213	1503
721	20	0	44	24	84	242		1581	25	8	1	75	221	1220
727	22	1	51	35	169	621		1591	25	6	19	74	201	1361
737	22	0	5	36	215	507		1601	25	8	0	77	220	1231
746	22	0	41	36	269	515		1610	25	6	29	79	191	1556
747	20	0	53	24	93	219		1621	25	12	0	77	220	1360
756	22	0	33	37	187	522		1630	25	3	57	80	163	1370
766	22	0	8	37	48	521		1639	25	8	10	77	210	1413
774	22	0	74	37	114	522		1648	25	6	17	83	203	1477
783	22	0	45	37	355	535		1657	25	5	56	88	276	1709
791	22	1	37	37	183	636		1666	26	2	2	82	204	1085
801	22	1	51	38	169	576		1674	26	6	6	87	180	1316
810	22	0	45	38	175	557		1683	26	5	5	87	227	1228
819	22	0	59	39	251	566		1692	26	11	11	89	227	1665
827	22	0	68	39	152	564		1699	26	6	6	92	207	1405
837	22	0	15	40	55	578		1709	26	7	7	94	235	1476
844	22	0	47	40	267	574		1717	26	8	8	95	237	1518
853	22	0	44	40	84	577		1728	26	8	8	96	238	1575
862	22	0	47	40	173	585		1737	26	6	6	94	197	1419
870	22	0	79	41	141	596		1746	26	5	5	91	269	1303
877	22	1	19	41	201	640		1758	26	5	5	93	193	1314
887	22	1	19	42	201	643		1772	26	3	3	96	197	1208
895	22	1	24	43	196	632		1785	26	1	1	103	200	1264
904	22	1	10	43	210	639		1798	26	5	5	99	215	1366
914	22	1	54	44	166	671		1809	26	10	10	97	206	1659
924	22	1	14	44	206	649		1825	26	8	8	103	237	1587
936	22	1	5	44	215	643		1837	29	2	54	182	94	1951
946	22	1	30	45	200	656		1837	26	12	12	105	224	1857
956	22	1	40	45	180	766		1849	26	8	8	105	215	1657
966	22	2	17	46	203	741		1859	26	5	5	107	234	1380
975	22	3	16	45	204	810		1869	26	5	5	110	222	1450
985	22	1	33	46	187	769		1879	26	4	4	110	218	1349
998	22	1	27	46	193	745		1886	26	8	8	110	251	1651
1010	22	3	54	46	166	945		1889	21	0	88	197	132	1884
1020	22	0	36	47	184	693		1893	26	3	3	115	246	1363
1032	23	2	17	48	203	774		1899	30	1	25	208	245	1892
1045	23	1	12	47	232	697		1899	29	1	1	214	221	1923
1055	23	4	3	48	217	788		1900	26	9	9	116	217	1782
1066	23	3	29	49	191	913		1908	26	1	1	117	291	1376
1076	23	2	2	50	222	737		1910	21	1	45	203	355	1925
1089	23	2	16	51	214	805		1914	26	4	4	120	232	1413
1097	23	1	12	51	232	754		1922	26	4	4	121	238	1417
1107	23	2	13	52	207	803		1929	26	5	5	121	231	1472
1119	23	2	1	51	221	754		1936	26	5	5	126	208	1558
1127	23	1	26	55	246	844		1946	26	6	6	126	239	1662
1139	23	1	2	56	222	812		1953	26	3	3	127	193	1449
1150	23	0	2	56	152	816		1962	26		11	127	224	1446

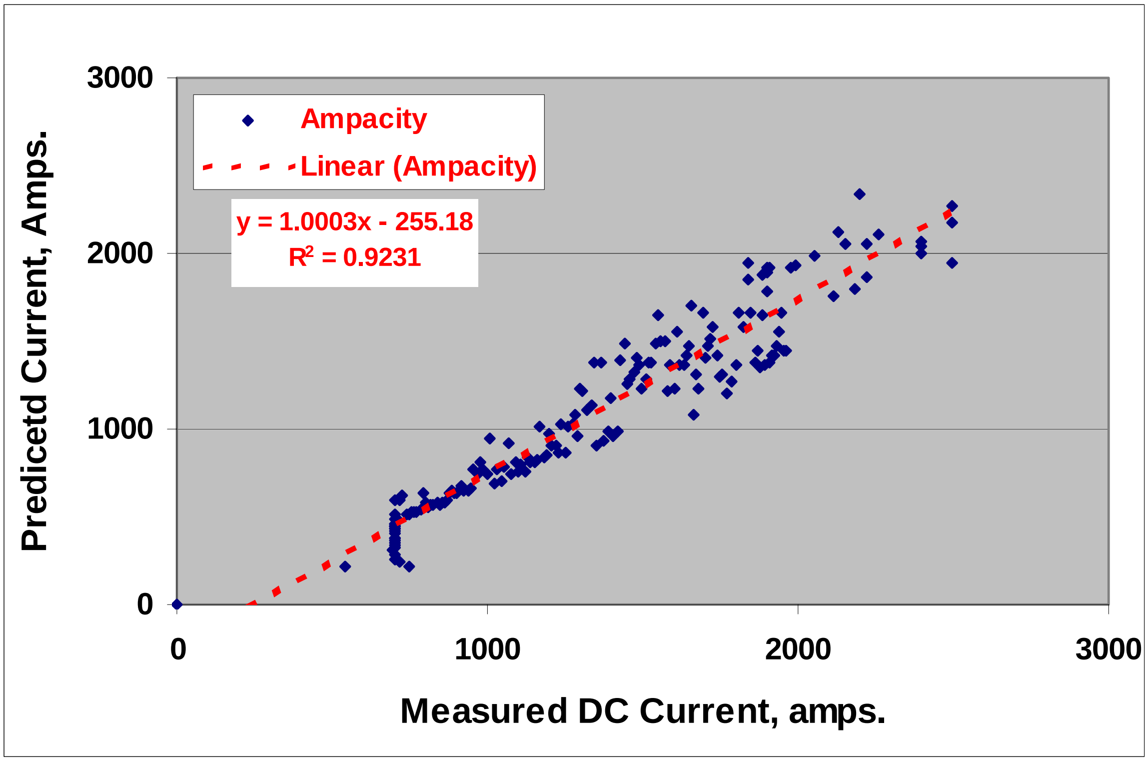


Figure 25- All Predicted VS measured current; IEEE Std 738 shows better agreement at temperatures above 1000^{0} C.

ACCR 1272 Conductor was rated at 2229 amps continuous at 210^{0} C and at 2402 amps emergency at 240^{0} C. The data shows the conductor was sometimes exposed to temperature higher than 240C and current above 2400 amps

6-2 IEEE VS CIGRE' Ampacity Model:

The CIGRE' 1997 model was used to compute current and to compare with the IEEE Std 736 used above- both programs were provided by the Valley Group Rate kit software. There are small differences in the method of calculations and literature indicates that the difference is small. Our calculations show that the difference in predicted current was < 0.8% and the two approaches agree very well:

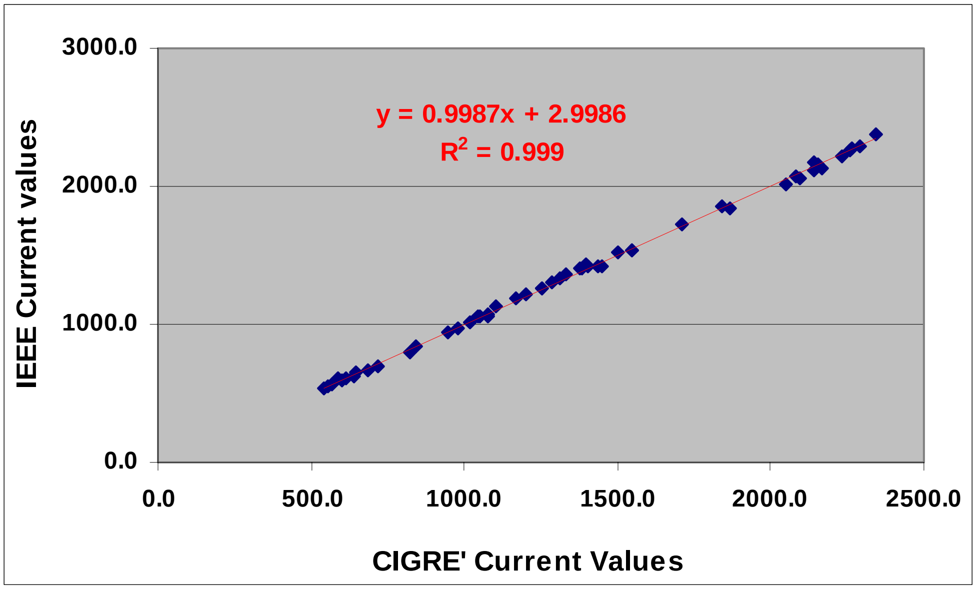


Figure 26- Comparison of Predicted Current values computed using both IEEE and CIGRE Ampacity models. Average difference between the two methods is about 0.89%.

7- Summary

ACCR 1272 conductor was successfully installed and tested at ORNL. It was thermally cycled from ambient to > 200^0 C for several hundred hours, using DC power supply. Measured temperature difference between conductor core and its surface was only several degrees at cycling temperatures in excess of 200^0 C. The wind speed appears to have a strong effect on cooling of the conductor

Data analysis shows that the measured conductor current agrees well with the IEEE thermal rating model predicted values. The conductor is rated at 2229 amps for continuous operation at 210^0 C and 2402 amps emergency at 240^0C. The CIGRE' model agrees well with the IEEE 736 model within 0.8%.

The conductor sag was stable during and after thermal cycling. Measured line tension agrees well with values computed using the strain summation method.

Both PLP and AFL accessories ran cool, < 120^0 C and show no visual damage.

Conductor was de- installed in June 2005, and sent to NEETRAC for testing and evaluation.

8- Appendix

8-1 Conductor Specs

Conductor Specs

Conductor Physical Properties		
Designation		1272-T13
Stranding		54/19
kcmils	kcmil	1272
	mm^2	644.5
Diameter		
Individual Core	in	0.092
Individual Aluminum	in	0.153
Core	In	0.46
Core diameter tolerance	in	+/- 0.005
Total Diameter		
Total diameter tolerance	in	+/- 0.014
Area		
Al	in^2	0.999
Total Area	in^2	1.126
Weight	lbs/ linear ft	1.392
Breaking Strength		
Core	Lbs	23, 622
Aluminum	Lbs	20,055
Complete Cable	000's lbs	43,677
Modulus		
Core	Msi	31.4
Aluminum	Msi	8.0
Complete Cable	Msi	10.6
Thermal Elongation		
Core		6
Aluminum		23
Complete Cable		17
Heat Capacity		
Core	W-sec/ft-C	28
Aluminum	W-sec/ft-C	520

Conductor Electrical Properties		
Resistance		
DC @ 20C	Ohms/mile	0.0700
AC @ 25C	Ohms/mile	0.0717
AC @ 50C	Ohms/mile	0.0787
AC @ 75C	Ohms/mile	0.0858
		0.0466
Geometric Mean Radius		
Inductive Ax		0.372
		0.0847
Capacitance Ax’s		

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Appendix A.4

ACCR 675-TW Kcmil Report

Composite Conductor Field Trial Summary Report: ORNL ACCR 675-TW Kcmil

Installation Date	November 2003
Field trial Location	Oak Ridge, Tennessee, USA

Organization	Oak Ridge National Laboratory
Point of Contact	John Stovall, ORNL
Installation Date:	November 2003
Conductor Installed	ACCR 675-TW
Length of line:	2,400 feet (731 meters)
Conductor diameter	0.901 inch, (22.9 mm)
Voltage	400 VDC
Ruling span length	600 feet, (183 meters)
Structure Type	Steel Poles
Instrumentation:	(1) Load cell (2) Current, voltage (3) Weather station (4) Sag (5) Thermocouples in conductor at 25 different locations. (6) Thermocouples in accessories at 50 locations.
Suspension Hardware	Preformed Line Product, THERMOLIGN^{TM} Suspension TLS-675TW-CE
Termination Hardware	Alcoa Compression Dead End B9085-C
Splice	Alcoa Full Tension Splice, B9095-D
Jumper	Alcoa Compression Terminal Connector- B9102-D
Insulator type	Polymer
Dampers	Alcoa Stockbridge Dampers- 1705-7
Results and Measurements	Full range of temperature tests from 30^{o}F – 412^{o}F (0^{o}C – 240^{o}C) with currents ranging from 0 to 1500 amps • Sag-temperature from -10^{o}C – 240^{o}C • SAG after 300 hrs exposure at high temperature • SAG after over 26 cycles from RT to 240 C (464 F) • Accessory temperature profile after repeated thermal cycles • Measured / predicted thermal rating • Conductor and accessory testing after thermal cycles

Acknowledgement:

This material is based upon work supported by the U.S. Department of Energy under Award No. DE-FC02-02CH11111. Any opinions, findings or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the U.S. Department of Energy. 3M Copyright, 2004

Table of Contents

Abstract:

Under DOE funding Agreement No. DE-FC02-02CH11111, ORNL jointly with TVA installed the 3M ACCR 675TW Conductor on a high temperature test line. The conductor was installed with commercial hardware developed for ACCR conductors. The line was 1200 feet (365 meters) long, and the ruling span was 600 feet (183 meters). Installation of the line was completed on November 6, 2003. The line was fully instrumented with (1) thermocouples in the conductor and accessories, (2) a CAT-1 system to measure tension and (3) a full weather station.

Oak Ridge National Laboratory subjected the line to severe thermal cycling up to 240 C and extended times under high temperature load. Analyzed sag values agreed with predicted models. Sag-temperature-current characteristics are predictable after repeated thermal cycles. Current values agreed with IEEE thermal rating prediction model.

After the line was taken down both conductor and accessories were tested and the results show that they maintained their strength with no degradation or damage. There was no change in electrical conductivity of the conductor.

1 -Background

Reliable high temperature performance is one of the key requirements for implementing new high temperature-low sag conductors. It is imperative to demonstrate in the field that the conductor and accessories can operate safely at high-temperature, under thermal cycling and without degradation. It is also important to demonstrate that the sag-temperature-current characteristics can be predicted after repeated thermal cycles.

Installation and operation of the composite conductor in field trials is typically not well suited for deliberately testing elevated temperature cycling because the thermal load is not easily controlled or predicted. The factors leading to high-temperature excursions include: line current loading under N-1 or N-2 contingencies, emergency conditions, wind, and solar exposure. Depending on these conditions, it can take a year or more for the conductor to experience a single emergency load to temperature greater than 200 C.

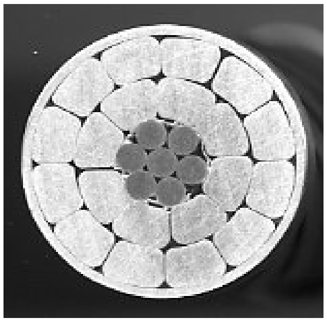
High-temperature exposure and thermal cycling with excursions of the conductor and accessories can be more easily achieved on a test line that operates at low voltage with a controlled current. Such a test line is able to approximately simulate forty years of emergency conditions in three months by implementing sufficient emergency cycles where the conductor temperature exceeds the rating temperature of 210^{o}C, (410^{o}F).

ORNL has built a fully instrumented low-voltage test line to evaluate the high-temperature operation of 3M ACCR conductors. Line instrumentations include mechanical tension, full weather station with anemometer, voltage, current, laser sensor to measure sag, and temperature thermocouples in multiple locations on the conductor and accessories.

This report summarizes ACCR 675TW conductor installation, testing and analysis at ORNL and post thermal cycling examination of the ACCR conductor and accessories.

Aerial view of the line

Towers



ACCR 675 TW

2- Installation and Conductor Stringing

2-1 Overview

A two span test line was constructed on the grounds of the Oak Ridge National Laboratory in Oak Ridge, Tennesse, as a part of a Department of Energy program. Oak Ridge National Laboratory subcontracted the line engineering and construction to the Tennessee Valley Authority, (TVA). The test line (Figure 2) consists of two 600 feet (183 meters) spans between a steel suspension pole and two guyed dual steel dead end poles. The test conductor forms a loop connected to a DC power supply located at one end of the line. Thermocouples were installed along the test conductor and on dead end, suspension and splice hardware to measure the temperature of these components during and after periods of high temperature operation.

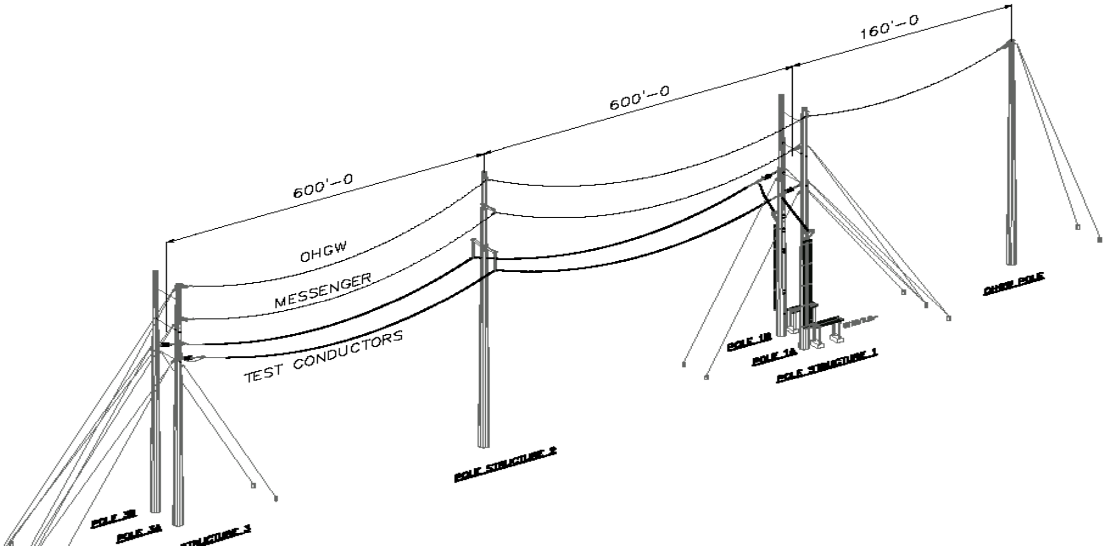


Figure 2- Line Layout and PCAT –1 system

2-2 Installation details:

The installation of the 675 TW ACCR followed the IEEE 524 installation guideline for overhead transmission conductors. The standard applies with the following requirements:

The only conductor stringing method recommended is the tension method. It is important that bending of the composite conductor during installation be carefully estimated to avoid damaging the composite core. If the combination of bending and tension exceeds the allowable core strength it could damage the conductor. Therefore stringing blocks and bull wheels are selected to keep the combined loads well below conductor core strength. Table 2 specifies 28” diameter stringing blocks and 36” diameter or larger bull wheels to meet such criteria. Lined blocks are recommended for use with ACCR. Other installation procedure and hardware are very similar to those used for either ACSR or ACSS. A PLP Distribution Grip was used to pull the conductor to sag and to install full tension splices. Sagging procedures are very similar to that of ACSR, the load cells on the CAT-1 System was used to verify the final sag tensions of the conductor. It is important to allow sufficient length of conductor to apply the permanent Alcoa dead end connector and assembly. The conductor grip was placed on the conductor 12 to 15 feet from the connection point to the insulator string. After the final sag tension was set, the dead ends were installed onto the ACCR.

Table 1- Installation hardware and Procedure Comparison

Installation Equipment	ACSR	ACCR
Stringing blocks	Yes	Yes (28”)
Bull wheels	Yes	Yes (54”)
Drum Puller	Yes	Yes
Sock splice	Yes	Yes
Conductor grip	Any	Distribution grips, DG
Cable spool	Yes	Yes (48” drums)
Cable cutter	Yes	Yes
Reel stands	Yes	Yes
Grounding clamps	Yes	Yes
Running ground	Yes	Yes

Installation Procedure	ACSR	ACCR
Cable stringing	Tension/ slack	Tension
Sag tensioning	Any	Line of sight-Dynometer
Dead ending	Any	DG grips with chain hoist
Clipping	Any	Any

The following images and those under the next section are typical examples of the installation details

Figure 3- Bull wheel tension of conductor during installation

2-3- CAT-1 Instrumentation:

A CAT-1 system with weather station was installed on one of the dead end structures to monitor the conductor tension and weather conditions (temperature, wind speed, and direction) at intervals of 1- minute. The conductor mechanical tension was measured using two 10,000 pounds load cells, Figure 4. The CAT-1 system also includes an anemometer to measure wind speed and direction and a net radiation sensor to measure ambient temperature and solar radiation. Data acquisition was done at 1 minute rate for all channels. The CAT-1 main unit is in a NEMA-enclosed, solar powered, data acquisition and processing unit

4-a- Load cell used to measure tension

4-b- CAT-1 System

4- c Net Radiation Sensor Measures-
No Load Conductor Temperature

Figure 4- CAT-1 system hardware details

Net Radiation Temperature (NRT) is measured by the NRS, Figure 3 below, which provides a simple method of combining ambient temperature with wind and solar effects to simplify measurements and rating calculations.

2- 4 Conductor and Accessories Temperature Measurements:

The temperature was measured using thermocouples as follows:

Thirty thermocouples were mounted at various locations along the span, including four thermocouples directly touching the composite core.

The other thermocouples were located on the conductor surface; however not all were active at the same time:

a. Eighteen thermocouples in three different ALCOA dead ends
b. Eight thermocouples in one ALCOA compression splice
c. Four thermocouples in a PLP THERMOLIGN^{TM} Suspension
d. Four thermocouples in Alcoa jumpers

A separate data acquisition system was used to collect the information from the thermocouples. To accommodate the multiplicity of points along the conductor and withstand the accumulated voltage drop, many fiber-connected, isolated measurement nodes were used. A thermocouple measurement node is fabricated using a multiplexer (ICPCON I-7018) and a RS-485-to-fiber modem (B&B FOSTCDR). Up to eight thermocouples are monitored per node. The node requires 120 VAC power and is data connected through a duplex fiber optic network. The multiplexer, fiber modem, and a power supply are housed in a Preformed Line Product enclosure.

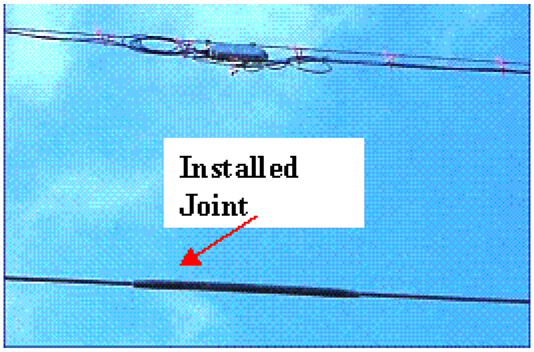
2-5 Controls

The line was operated under constant either current and / or constant conductor temperature with thermal cycles lasting from less than one hour to several days.

2-6 Accessories:

Compression type dead end and splice made by Alcoa were installed. The following specific parts were used: (1) Four ALCOA compression dead ends; part/ drawing # B9085- those dead ends consist of both direct core gripping parts and conductor gripping sleeve. (2) One ALCOA full tension splice part# B9095-D; it has the same design as the dead-end for both direct core gripping and conductor. (3) Two high-temperature commercial PLP THERMOLIGN^{TM} Suspensions, (240 C conductor temperature), Part # TLS-675TW-CE. (4) Six Alcoa terminal connectors; part# B9102-D; those are all

Aluminum sleeve parts (5) Four Alcoa Stockbridge dampers, part# 1705-7



5- a compression splice

5-b Terminal connector / jumper installation

5-c Alcoa compression dead end

5-d PLP suspension system

Figure 5 Examples of both installed Alcoa compression accessories and PLP suspension

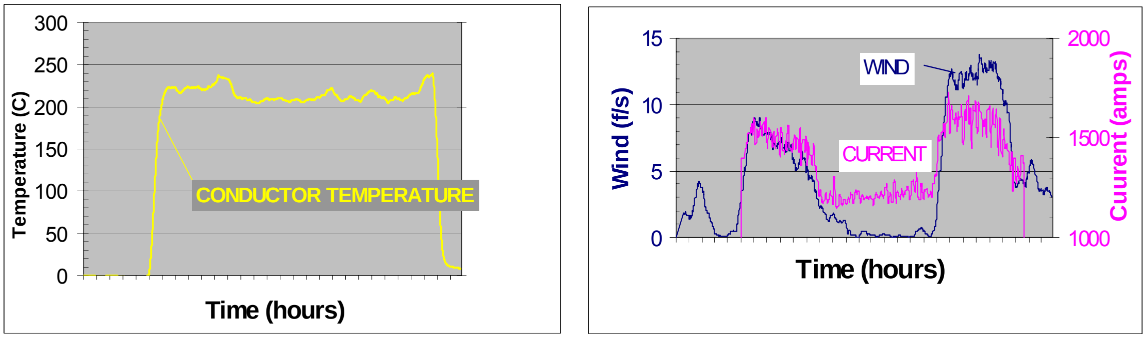
3- Thermal Cycles and High Temperature Exposure:

The 675TW conductor was thermally cycled from November 2003 to March 2004 with a total of 32 cycles ranging from one hour to twenty hours; see Table 2. Cycles were either in temperature control where the conductor was held at constant temperature (210-240 C) for the duration of the cycle, or in current control, where the conductor was held at a constant current for the duration of the cycle. The power supply used to energize the line had a dual rating of 400 Vdc and 5000 amps or 600 Vdc and 3750 amps. The input voltage to the power supply was 4.16 KV, 3-phase. A dry-type ABB transformer was used to step down the voltage from a 13.8 KV distribution line.

Figure 6-a, b, shows the core temperature of the conductor during a typical thermal cycle in temperature control mode along with current and wind speed. The temperature is maintained at 210-240 C by controlling the current from 1000 amps to 1800 amps while the wind fluctuates between 0 f/s and 15 f/s, Figure 6-b.

Table 2- Details of Thermal/ Current cycling

Cycles	Date	Run Hours	Hours> 200C	Total Hours >200C	Comment
1	11/12/2003	2	0	0	T controlled, 200C+
2	11/13/2003	6	6	6	T controlled, 200C+
3	11/14/2003	5.5	5.5	11.5	T controlled, 200C+
4	11/17/2003	6	6	17.5	T controlled, 200C+
5	11/18/2003	6	6	23.5	T controlled, 200C+
6	12/1/2003	6	6	29.5	T controlled, 200C+
7	1/13/2004	8	8	37.5	T controlled, 200C+
8	1/14/2004	8	8	45.5	T controlled, 200C+
9	1/16/2004	8	8	53.5	T controlled, 200C+
10	2/12/2004	1		53.5	T controlled, 200C+
11	2/18/2004	3	3	56.5	T controlled, 200C+
12	2/19/2004	7	7	63.5	T controlled, 200C+
13	2/20/2004	5	5	68.5	T controlled, 200C+
14	2/23/2004	7	7	75.5	T controlled, 200C+
15	2/24/2004	7	7	82.5	T controlled 200 C+, Rained, 0.1"
16	2/25/2004	7	7	89.5	T controlled 200C+, Windy
	2/26/2004			89.5	T controlled 200C+, Snow
17	2/27/2004	6.5	6.5	96	
18	3/1/2004	6	6	102	T controlled 200C+ Windy,
19	3/2/2004	9	9	111	T controlled 200C+, Rainy day. 0.69"
20	3/3/2004	9	9	120	T controlled 200C+, Foggy morning
21	3/4/2004	16	16	136	T controlled, 200C+,Overnight run
22	3/5/2004	16	16	152	T controlled, 200C+,Overnight run
23	3/10/2004	14	14	166	T controlled 200C+, Overnight run
24	3/11/2004	20	20	186	
25	3/12/2004	0.5	0	186	T controlled, 200C+
26	3/22/2004	6.5	6.5	192.5	T controlled, 200C+
27	3/23/2004	14	0	192.5	Constant current, 1000 A
28	3/24/2004	24	0	192.5	Constant current Midnight - 4 PM @ 1000 A; 4 PM - Midnight @ 750 A
29	3/25/2004	19.5	0	192.5	Constant current, Midnight - 4 PM @ 750 A; 4 PM - 7:30 PM
30	3/26/2004	17	5	197.5	Constant current, 6:40 AM to Midnight @ 1200 A
31	3/27/2004	24	8.5	206	Constant current, Midnight to 10:25 AM @ 1200 A;10:25 A to Midnight @ 575 A
32	3/28/2004	12	0	206	Constant current, Midnight to Noon @ 575 A



6-a—Core temperature

6-b- Current and wind speed

The

Figure 6- Example of conductor constant temperature cycle with wind and current

For 24 hours followed by 575 amps for another 24 hour. In this case, the conductor temperature fluctuates between 230C and 50 C.

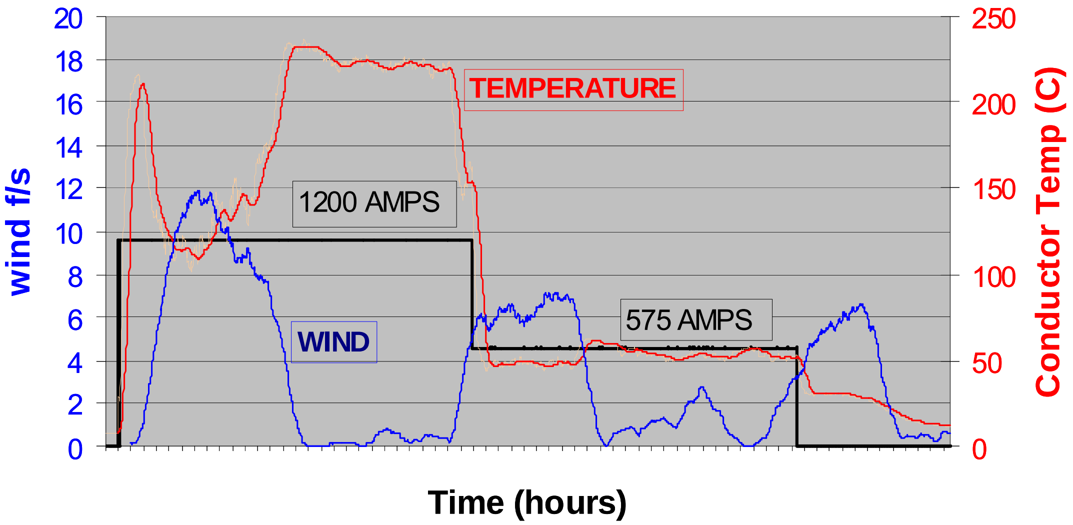


Figure 7-Typical constant current cycle for 675 TW

4- *Measured and Predicted Line Tension and Sag:*

The following are two video frames showing the line before being energized and at maximum sag after application of current.

11:29:08 – Before

11:54 – Maximum Sag

Figure 8- Observation of line sag changes during current cycling

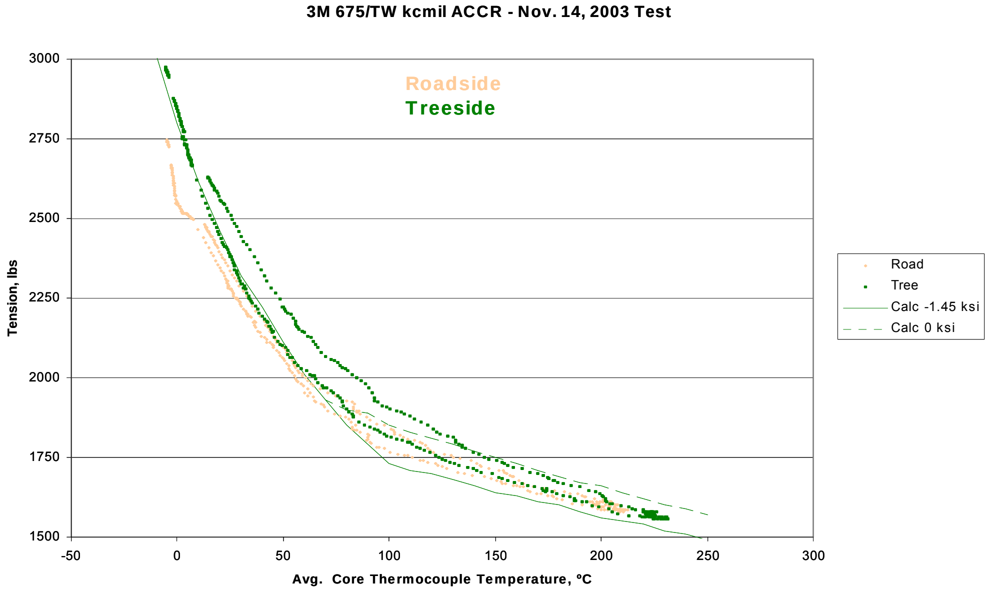


Figure 9- Measured VS predicted tension

The sag was predicted with two methods: the Strain Summation Method to account for the full loading history, and the more commonly used Graphic Method, (Alcoa SAG-10). The Strain Summation Method of Sag-Tension Calculation takes into account both creep and wind conditions as a function of time. A conductor data file was created based on stress strain tests performed by NEETRAC on the conductor. Compressive stresses of 0 and 1.45 Ksi were used to compute sag. Predicted sag values appear to agree reasonably well within 2” sag value, see figure 9 and 10.

Data generated from November 2003 to March 2004, after additional 192.4 hours exposure at > 200C is shown below in Figure 10. The data shows no change in the test line and conductor as compared to its the initial performance in November (Figure 9). There has been virtually no creep since Nov. 14/03; see figure 11

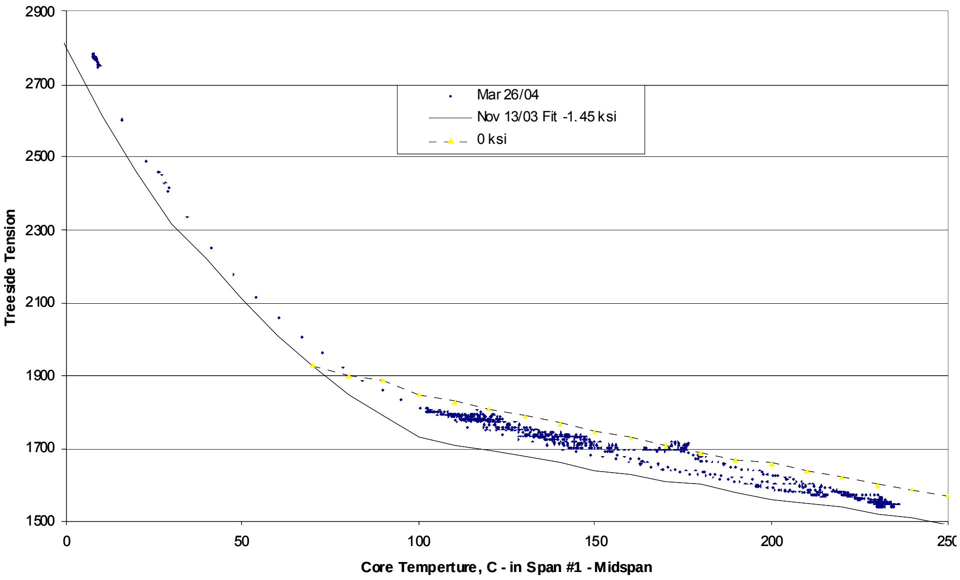


Figure 10- Measured and predicted span tension (tree side) VS conductor core temperature after 192.4 hours above 200 C

5- Additional Conductor Field Test data

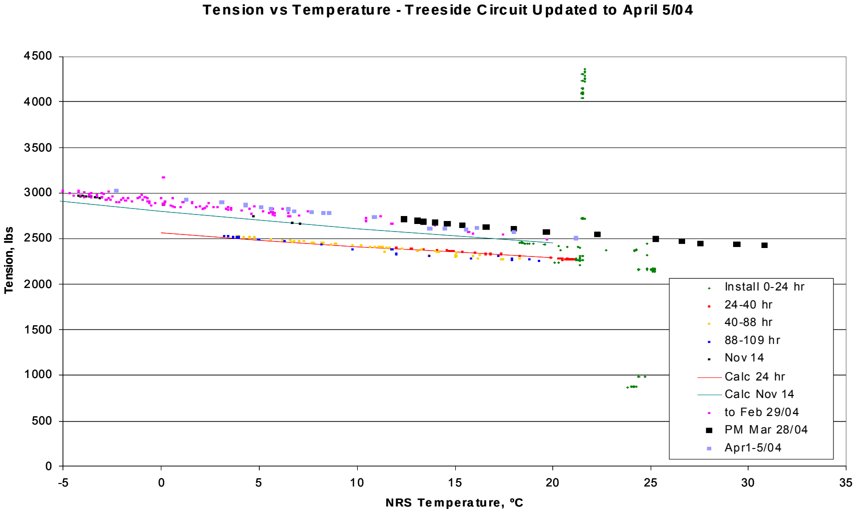


Figure 11- ACCR 675 TW showing almost no creep after 192.4 hours above 200 C

The next set of graphs 12, 13 show effect of both ice and rain on the conductor line tension. Ice build up produced a 300 lbs increase in tension for about 17 hours, Figure 13.

There was no effect of rain on either conductor temperature or tension when line was energized above 200C. The PCAT test line sag remained stable during the field trial. High temperature was negligible.

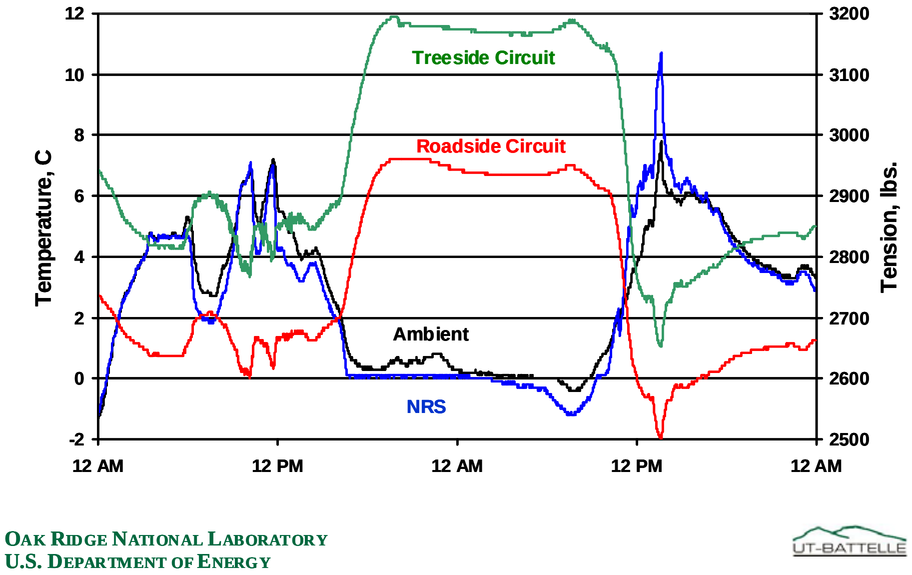


Figure 12- Ice build up for 17 hours on ACCR 675 TW on February 15- 16, produced about 300 lbs increase in line

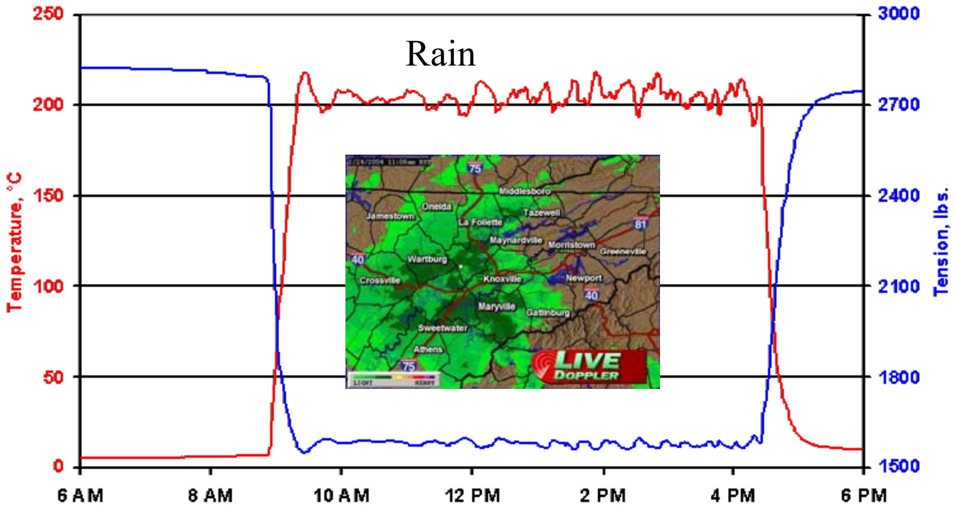


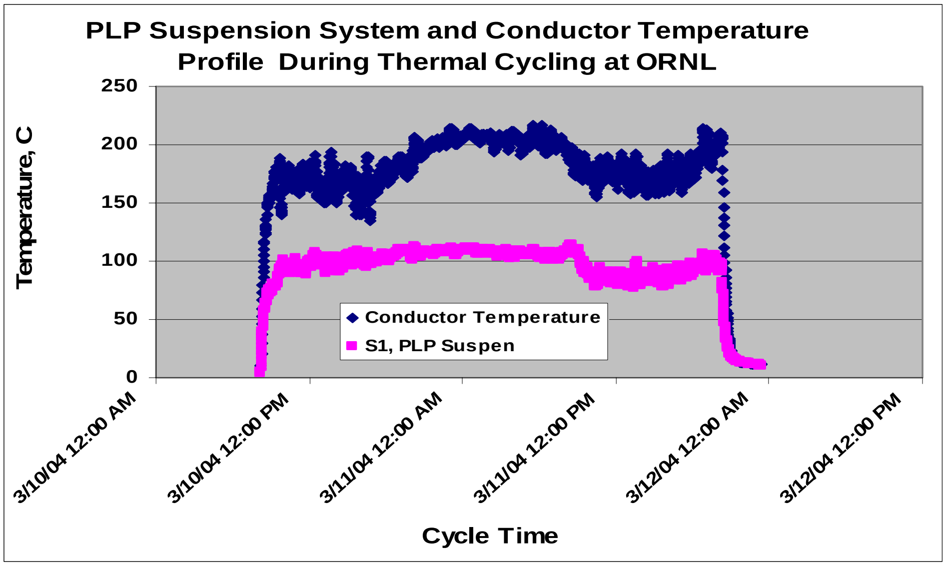
Figure 13- Rain on February 24, 2 hour shower (0.1”) had no effect on conductor temperature)

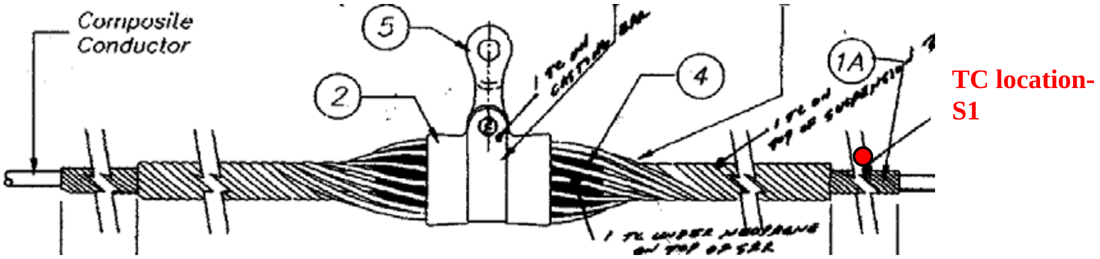
6- Accessories Response at High Temperature:

Over 300 hours of high temperature operation were performed under either temperature or current control. The line was subjected to a range of weather conditions during thermal cycling (-10 C to 250 C, wind, rain, and ice). All accessories performed well; maximum accessories temperature remained under 140 C as illustrated in Figures 15- 17.

6-1 PLP Accessories:

PLP THERMOLIGN^{TM} Suspension System ran under 100 C during high temperature cycling





End of inner rod TC location

Figure 14- PLP THERMOLIGN^{TM} Suspension ran cool at conductor temperature of > 200^0 C

6-2 Alcoa Accessories:

All Alcoa compression accessories showed normal behavior with no over heating during conductor thermal cycling; examples are shown in figures 15 and 16.

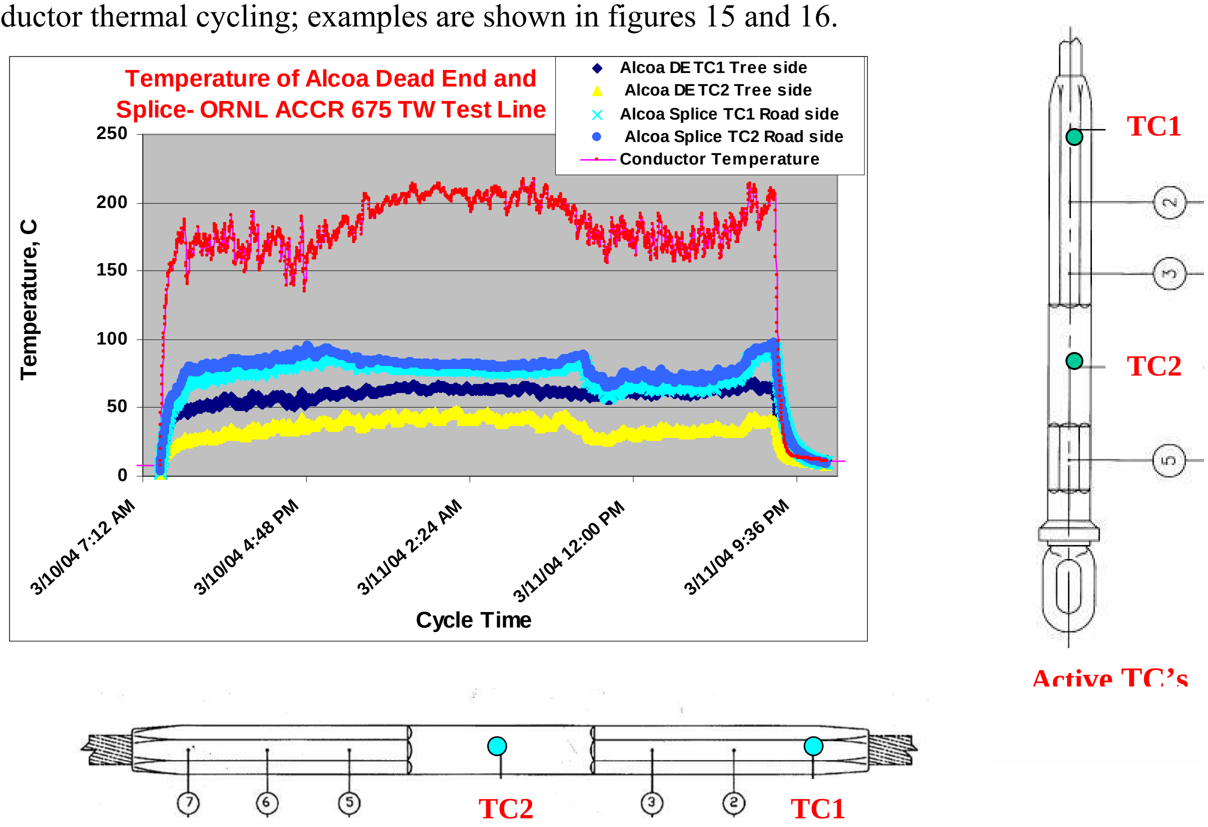


Figure 15 Alcoa dead-end and splice temperature stayed below 100 C while conductor was cycled to above 200 C. TC locations are in green cicles; Locations 1 and 4 are for TC1 and TC2

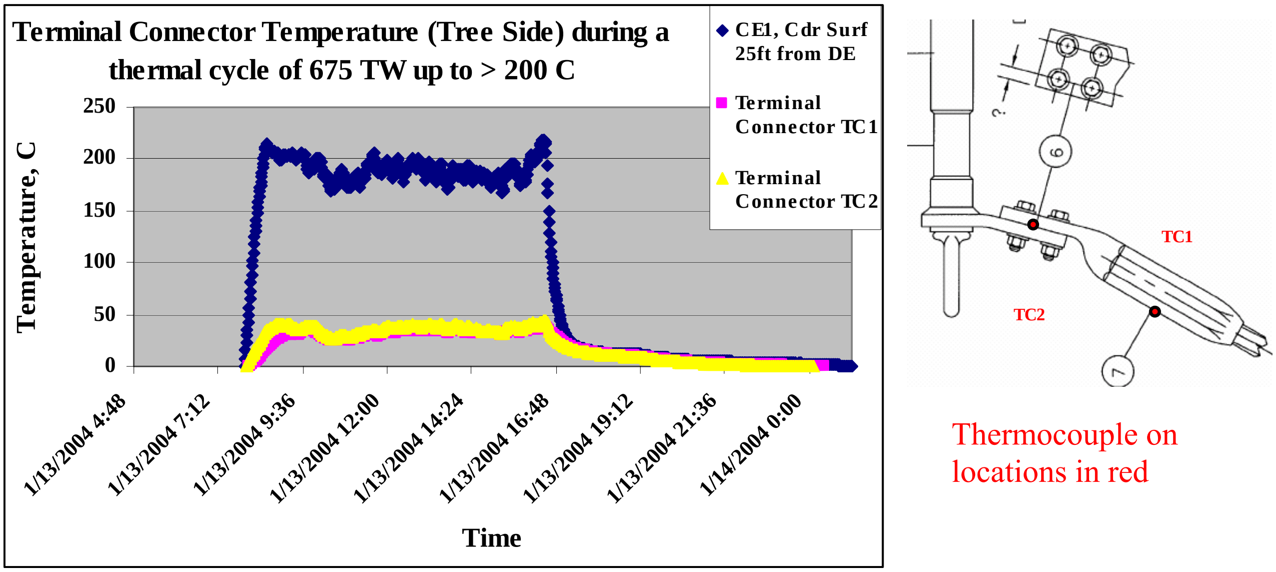


Figure 16- Alcoa Compression terminal connector temperature- connector ran < 55 C when conductor was at 200 C

7- Ampacity and Thermal Rating of Conductor

Conductor current was computed using IEEE STD 738-1993- “Standard for Calculating the Current Temperature Relationship of Bare Overhead Conductors**”.** Steady State data, where both conductor current and wind speed were constant, was selected. Wind speed data was averaged over 30 minute intervals. The following input parameters were used in the model calculations:

Emissivity: 0.27 (measured by ORNL- see details in appendix)
Solar absorption: 0.5
Conductor elevation: 800 feet
Conductor latitude: 30 degrees
Total solar flux: 1 w/ft^2
Thermal conductivity: 0.01 w/ft K
Sun altitude: 54 degrees

The IEEE current prediction model provides good agreement with actual line-measurements current over a range of current from 400 to 1200 amps with the conductor in the 60 C to 230 C temperature range, Figure 18

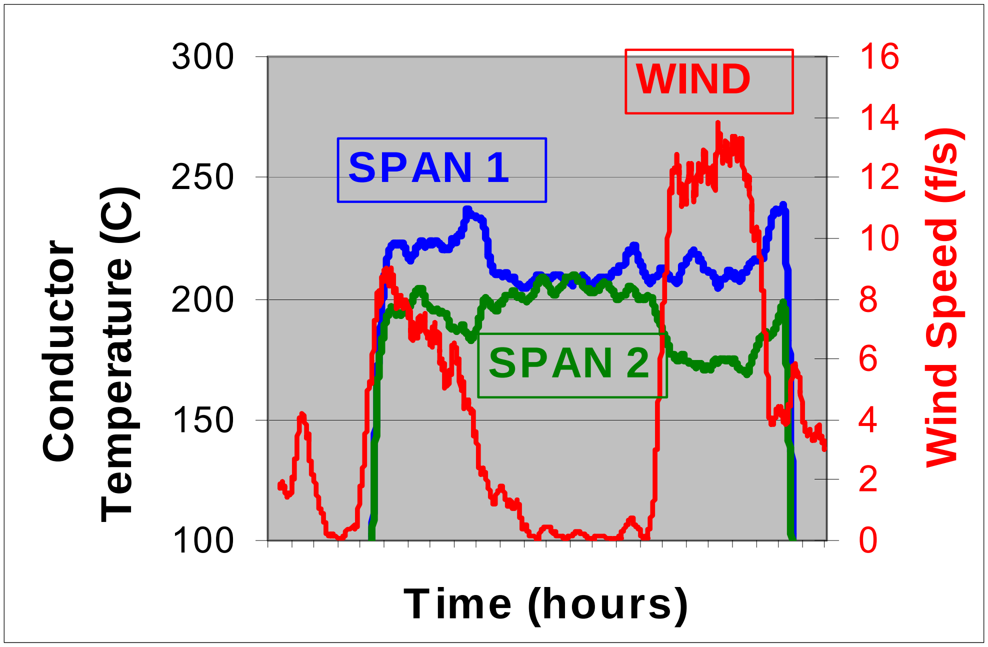


Figure 17- An example of steady state conductor temperature and wind speed data used in the model

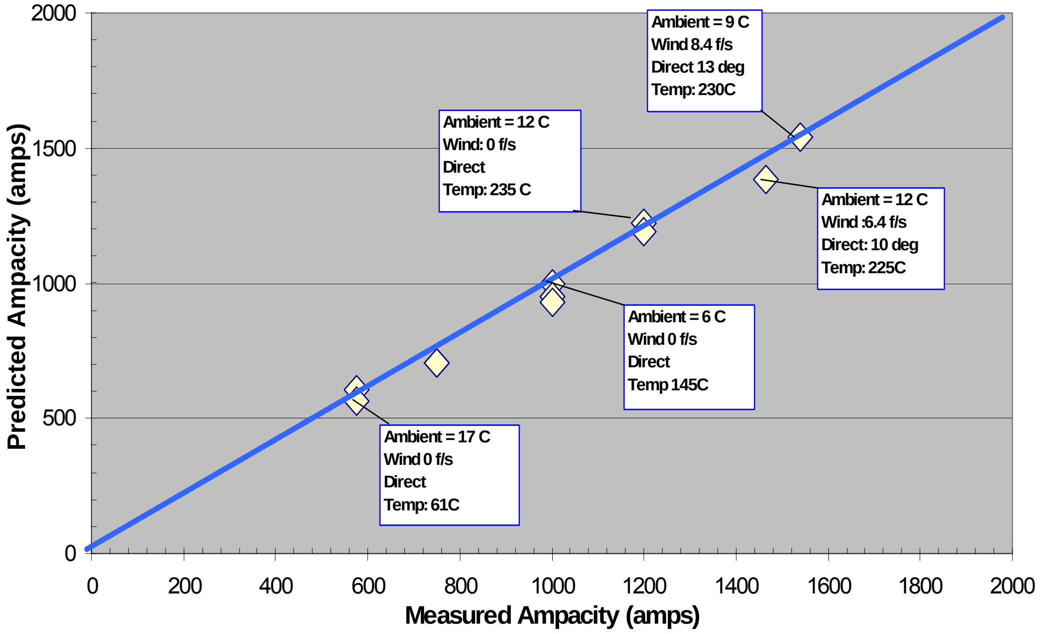


Figure 18-Good agreement between Measured and predicted current. Predicted values were computed using IEEE ampacity rating steady state model

8- Post ORNL Conductor and Accessories Evaluation

The following tests & measurements were carried out on the conductor and accessories after thermal cycling at ORNL:

8-1 Conductor tensile tests:

Three samples from the “free-span” conductor were terminated using cast-resin terminations. Clamps were used to preserve the as-received position of the conductor layers until the resin cured. The sample preparation method ensures that the laboratory tensile test loads each conductor strand in the same manner as a field overloads, and thereby measures the in-service conductor strength. Free conductor between the end fittings is 20 feet (6 meters).

A sample from the free-span section was terminated with cast-resin using a process that ensures that each conductor layer and strand is not displaced from its in-service position. The 1999 Aluminum Association guide for conductor stress-strain testing was followed with the exception of special values for the elastic properties of the metal matrix composite (MMC) core were used instead of values for steel core used in ACSR conductors. The core strand from another sample is used to measure core stress-strain, and determine the elastic properties of the composite conductor.

The conductor maintained its strength after thermal cycling at above 200C. The average of five measurements is 109 % RBS as shown in Table 3.

Table 3- Conductor test data

Sample	**Breaking load, Lbs**	**% RBS**	**Failure Mode**
04121T1	24,770	110	All strands fractured in the gage section
04121T2	25,430	113	All strands fractured in the resin fitting
04121T3	22,780	101	All strands fractured in the gage section next to a drilled thermocouple
Stress- Strain-conductor	25,250	112	Mid span break, all strands failed
Stress Strain-Core	12,820	111	Mid span break, all strands failed

8-2 Conductor Stress-strain:

Stress-strain results are similar to results from the same conductor prior to the field test. The principal difference is that creep during the 30% load hold phase is less on the field sample, apparently because the field loads caused the initial creep to be removed from the conductor as shown in Figures 19 to 21.

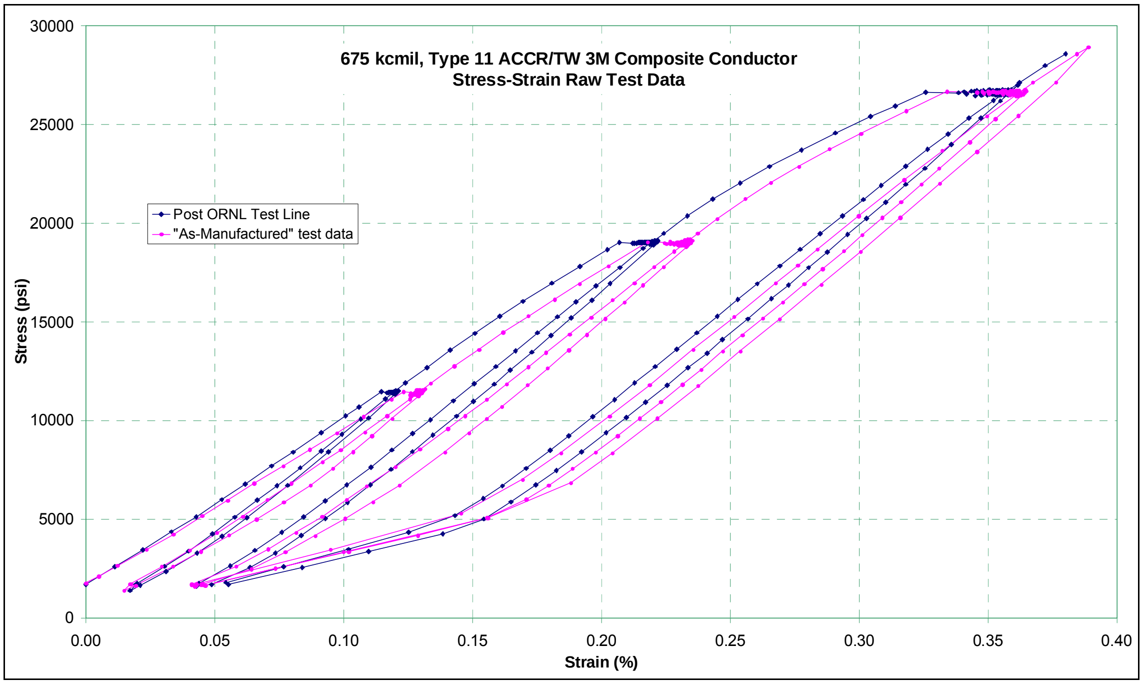


Figure 19- Plot of raw data recorded during conductor stress-strain test (blue), Agrees with data for conductor tested from same lot before the field test

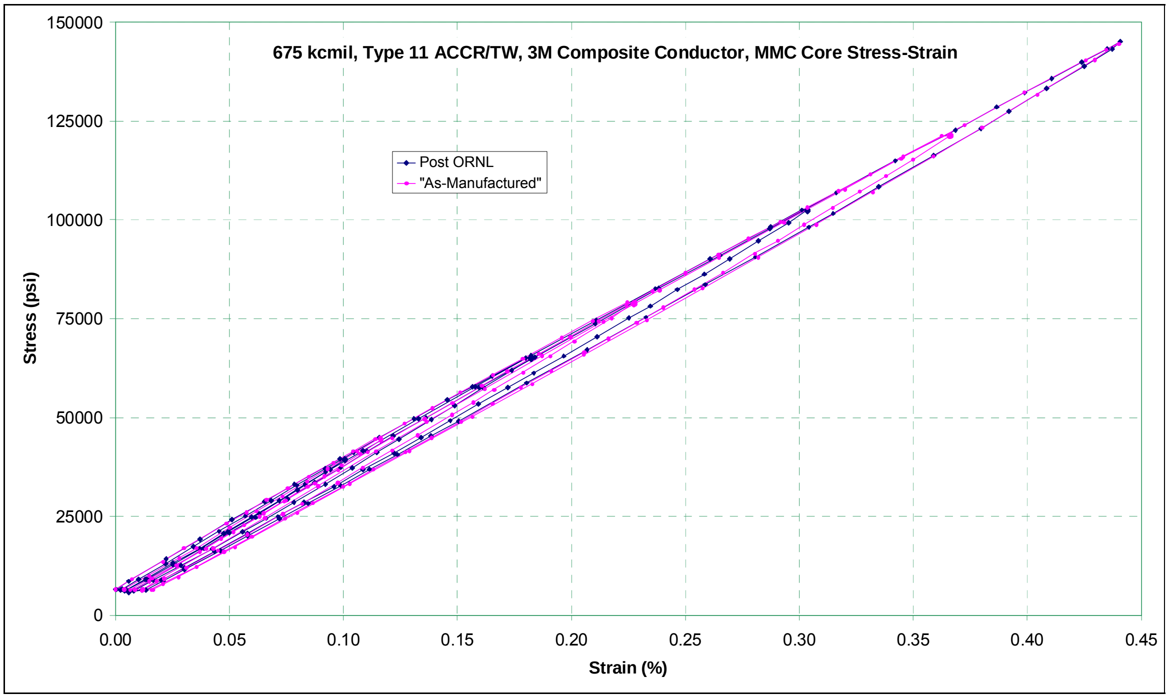


Figure 20- Core stress-strain shows essentially no change due to field test

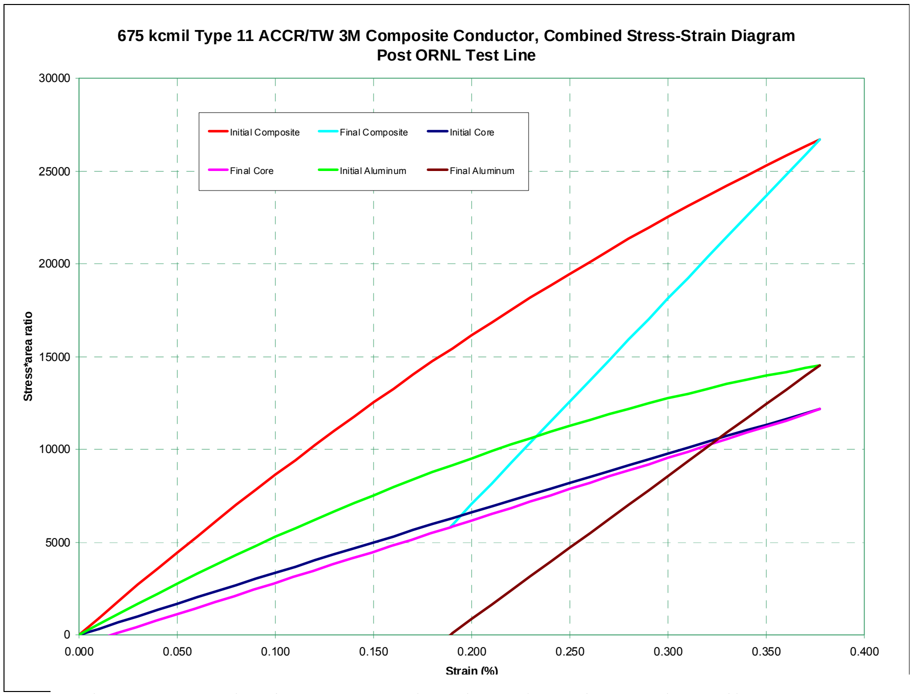


Figure 21- Final stress strain plot after thermal cycling

8-3 Conductor resistance test:

Welded equalizers were installed at each end of a 22-foot long sample from the free-span section. A second set of voltage equalizers in the form of tightly wrapped solid copper strands are applied nominally 20 feet apart in the test section. The sample is placed on a flat surface, and pulled with sufficient tension to remove any residual curvature in the conductor. Tension was about 200 – 300 lb. A digital low-resistance Ohmmeter was used to make a 4-wire resistance measurement for the conductor section between the two voltage equalizers. A digital multi meter was used to verify that the sample was electrically isolated.

22- a- Power connection to sample

22- b Sample-tensioning device

Figure 22- Set- up for conductor resistance measurements post ORNL field-testing

Conductor resistance for an average of 5 readings on a 20 feet long sample was 0.1332 Ω/mile at 20°C; it is close to the conductor resistance of 0.1346 Ω/mile at 20° C before thermal cycling.

8-4 Connector tensile tests:

8-4-1 Alcoa compression accessories

Two dead-ends and two splices were provided with cast resin fittings at free ends

The procedure preserves the “as received” position of the conductor components, and thereby assures that the breaking strength is the same as existed when the samples were in service on the test span.

Both splice and dead end maintained their load carrying capability of 100% RBS or more; details in table below

Table 4- Connector tensile tests

Sample	Breaking Load, Lbs	% RBS	Failure Mode
04121SP1 (Splice)	24,010	107	All strands fractured at the resin fitting
04121SP2 (Splice)	24,530	109	All strands fractured ~5” inside splice
04121DE1 (Dead end)	24,730	110	All strands fractured ~6” inside dead end
04121DE2 Dead end)	22,330	99	All strands fractured ~5” inside dead end

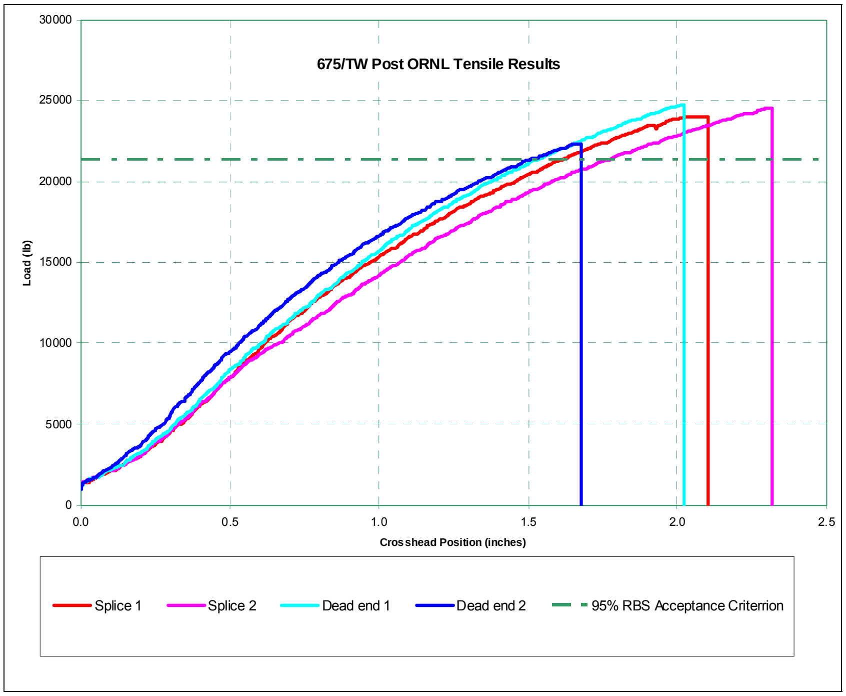


Figure 23 Tensile test data for accessories post ORNL Cycling current cycling

8-5 PLP Suspension:

Visual examination of the suspension components showed neither fatigue nor wear damage; conductor did not distort. Conductor segments which were inside the suspension were pulled in tension and gave 24,740 Lbs (110% RBS) load to failure, conductor failed in an area that was not under the suspension assembly

8-6 Connector Microscopic Examination:

One dead end and one splice were dissected using a milling machine to split the aluminum sleeve and reveal the internal splice components. Correct installation is verified by observing proper placement of the core grip, proper conductor preparation, and proper injection of inhibitor compound prior to compression.

The dissections and inspections showed good workmanship for core and aluminum insertion depth, component placement, and the crimping operation. Both conductor and accessories gave >100% RBS. It was however noticed that the center cavity contained no oxide inhibitor compound, showing that this step was omitted. Compound was applied liberally on the conductor OD, so this is not a serious issue for a short-term, field test Nevertheless installation instructions stipulate that the center cavity should be filled with oxide inhibitor compound through an injection port. There is no evidence that the conductor was wire-brushed prior to splice installation. AFL requires wire- brushing of the conductor OD only in cases where the connector is installed on weathered conductor. Proper wire brushing and the use of inhibitor compound have been reinforced in the installation guide.

9- Summary

ACCR 675 TW conductor was installed successfully on ORNL- PCAT Line using commercial hardware and normal installation procedures. The conductor and accessories were thermally cycled from ambient to > 200C for several hundred hours, using DC power supply and as high current as 1500 amps. The measured sag matched the SAG-10 prediction. Data analysis shows that the measured conductor current agrees well with the IEEE thermal rating model predicted values. After-de installation the conductor and accessories were tested for residual strength and degradation. Residual strength exceeded 100% RBS and neither conductor nor accessories showed any signs of damage. Conductor resistance after cycling is equivalent to that of conductor not exposed to thermal cycling

10- Appendix

10-1 Conductor Specs (Table 1)

Conductor Physical Properties		
Stranding		20/7
kcmils	kcmil	676
Area Fraction Core	%	10.25%
Weight Fraction Core		12.50%
Diameter		
indiv Core	in	0.105
indiv Al	in	
Core	in	0.315
Total Diameter	in	0.902
Area		
Al	in^2	0.5309
Total Area	in^2	0.5915
Weight	lbs/linear ft	0.726
Breaking Strength		
Core	lbs	11,564
Aluminum	lbs	10,923
Complete Cable	000's lbs	22,487
Modulus		
Core	msi	31.4
Aluminum	msi	7.6
Complete Cable	msi	10.1
Thermal Elongation		
Core	$10^{-6}/C^{o}$	6.35
Aluminum	$10^{-6}/C^{o}$	23.00
Complete Cable	$10^{-6}/C^{o}$	17.69
Heat Capacity		
Core	W-sec/ft-C	13
Aluminum	W-sec/ft-C	275
Conductor Electrical Properties		
Resistance		
DC @ 20C	ohms/mile	0.1317

AC @ 25C	ohms/mile	0.1348
AC @ 50C	ohms/mile	0.1481
AC @ 75C	ohms/mile	0.1615
Geometric Mean Radius	ft	0.0355
Reactance (1 ft Spacing, 60hz)		
Inductive Xa	ohms/mile	0.4052
Capacitive X'a	ohms/mile	0.0973

10-2 Detailed Resistance Data:

NEETRAC Project No. 04-121					
AVO (Biddle) DLRO, Calibration Control # CQ1097					
Temperature coefficient for resistance:	0.0036				
Resistance measurement on a 20' gage section of 675 ACCR/TW setup in the tensile room on the MTS frame, welded equalizers, pulled to ~200 lbs tension w/a come-a-long					
These readings taken manually 10/14/04 @ 9:54 am					
Conductor Temperature:	21.5	deg C			
Test Section:	20.000	ft			
Resistance Readings	506.8	µΩ	At	21.5	deg C
	506.7	µΩ	At	21.5	deg C
	506.7	µΩ	At	21.5	deg C
	506.73	µΩ	At	21.5	deg C
Ω/ft:	2.5337E-05	Ohm/ft	At	21.5	deg C
Ω/ft:	2.5200E-05		At	20.0	deg C
Ω/mi	0.13378	Ohm/mi	At	21.5	deg C
Ω/mi @ 20C:	0.13306		At	20.0	deg C
These readings taken manually 10/14/04 @ 10:32 am					
Conductor	21.8	deg C			

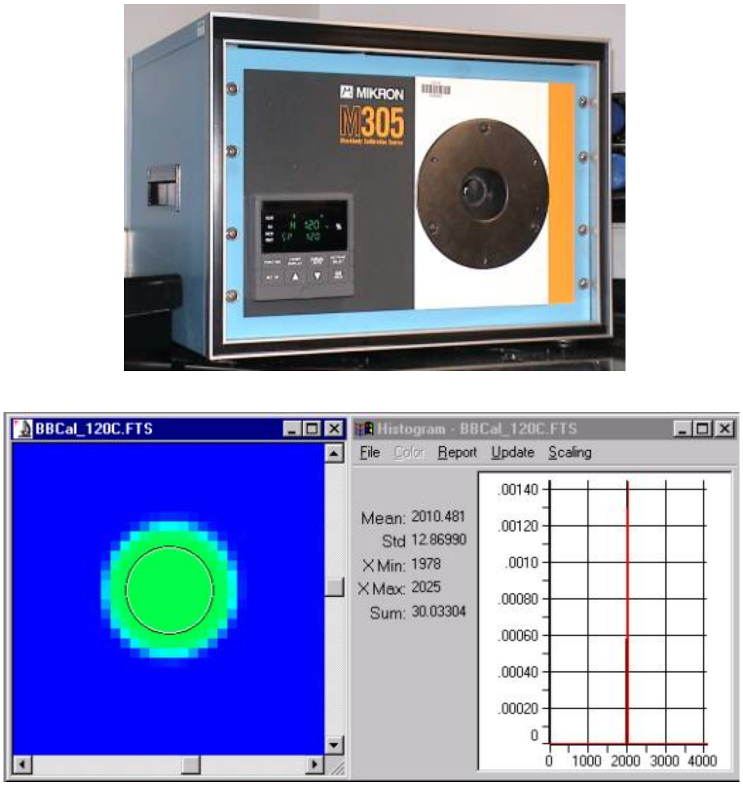
Temperature:					
Test Section:	20.000	ft			
Resistance Readings	507.4	μΩ	At	21.8	deg C
	507.4	μΩ	At	21.8	deg C
	507.3	μΩ	At	21.8	deg C
	507.37	μΩ	At	21.8	deg C
Ω/ft:	2.5368E-05	Ohm/ft	At	21.8	deg C
Ω/ft:	2.5231E-05		At	20.0	deg C
Ω/mi	0.13394	Ohm/mi	At	21.8	deg C
Ω/mi @ 20C:	0.13322		At	20.0	deg C

These readings taken manually 10/14/04 @ 10:53 am					
Conductor Temperature:	21.8	deg C			
Test Section:	20.000	ft			
Resistance Readings	507.4	μΩ	At	21.8	deg C
	507.4	μΩ	At	21.8	deg C
	507.3	μΩ	At	21.8	deg C
Average	507.37	μΩ	At	21.8	deg C
Ω/ft:	2.5368E-05	Ohm/ft	At	21.8	deg C
Ω/ft:	2.5231E-05		At	20.0	deg C
Ω/mi	0.13394	Ohm/mi	At	21.8	deg C
Ω/mi @ 20C:	0.13322		At	20.0	deg C
These readings taken manually 10/14/04 @ 2:34 pm					
Conductor Temperature:	21.9	deg C			
Test Section:	20.000	ft			
Resistance Readings	507.4	μΩ	At	21.8	deg C
	507.4	μΩ	At	21.8	deg C
	507.5	μΩ	At	21.8	deg C
Average	507.43	μΩ	At	21.8	deg C
Ω/ft:	2.5372E-05	Ohm/ft	At	21.9	deg C

Ω/ft:	2.5235E-05		At	20.0	deg C
Ω/mi	0.13396	Ohm/mi	At	21.9	deg C
Ω/mi @ 20C:	0.13324		At	20.0	deg C
These readings taken manually 10/14/04 @ 4:52 pm					
Conductor Temperature:	21.7	deg C			
Test Section:	20.000	ft			
Resistance Readings	506.9	μΩ	At	21.8	deg C
	507.0	μΩ	At	21.8	deg C
	506.9	μΩ	At	21.8	deg C
Average	506.93	μΩ	At	21.8	deg C
Ω/ft:	2.5347E-05	Ohm/ft	At	21.65	deg C
Ω/ft:	2.5210E-05		At	20.0	deg C
Ω/mi	0.13383	Ohm/mi	At	21.65	deg C
Ω/mi @ 20C:	0.13311		At	20.0	deg C
Errors:	Gage length	0.05%			
	Instrument	0.20%			
	Temperature	0.18%			
RMS Error:		0.27%			
Average, all readings:	0.13317	Ω/mi	At	20.0	deg C
3M nominal	0.13170	Ohm/mi	At	20.0	deg C

10-3 Emissivity Measurements:

Oak Ridge National Laboratory measured various 3M composite conductor emissivity using IR Imaging. A calibrated IR Camera and Mikron M305 Blackbody calibration source were used. Graph 24 shows the hardware used; the calibrated black body target was multiplied by various emissivity values until a good fit occurs with the conductor received signal. Such fit yielded an average emissivity value of 0.27 within +- 2%



Mean: 2010.481
Std 12.86990
X Min: 1978
X Max: 2025
Sum: 30.03304

Figure 24 Calibrated IR Camera and Mikron M305 Blackbody calibration source used for measuring emissivity

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Appendix B

Variability of Conductor Temperature in a Two Span Test Line

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Document for CIGRE TF 12-6 (B2), October 21, 2004

Variability of Conductor Temperature in a Two Span Test Line

Tapani O. Seppa	Robert Mohr	Herve Deve	John P. Stovall
The Valley Group, Inc.	The Valley Group, Inc.	3M Company	Oak Ridge National Laboratory

Background

A large number of prior reports have indicated substantial temperature variability within a single span in test lines and significant variation of temperature between point measurements in adjacent spans. More anecdotal evidence, e.g. in the discussion records of the Proceedings of the IEEE Panel on Dynamic Line Ratings on July 20-21, 1982, indicate that, at high temperature, longitudinal temperature variation of 10-25^{o}C had been observed in a single span. Accurate documentation of such variation is generally not available.

It is also generally recognized that the tension and sags of a line section between two dead-ends should be a function of the average temperature of the conductor. Observations have generally shown a good correlation between measured temperatures and sags, but high quality data for comparisons has typically not been available.

Because the high temperature conductor tests at the Oak Ridge PCAT facility are extremely well instrumented, these tests can provide answers to the above questions.

Powerline Conductor Accelerated Testing Facility (PCAT)

Testing Facility Description:

The Powerline Conductor Accelerated Testing facility (PCAT) at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee is an outdoor facility for thermal stress and age characterization tests of power line conductors, [1,2]. The facility includes a 2MW DC power supply fed by a 13.8kV/4160V transformer which can vary the loading of the conductor under test up to 400 Vdc and 5000 Adc.

Figure 1: Aerial view of PCAT facility

The test line is instrumented to measure the conductor's tension, clearance, temperature and environmental conditions (e.g., wind, solar, ambient). Surface and core temperatures are measured by means of thermocouples at multiple locations along the test line. The facility consists of three 161kV-rated steel transmission structures, with two tubular steel poles at each of the two dead-end locations and one in the center with steel davit arms. The test line consists of two circuits, referred to as “road side” and “tree side”, each is 366 m (1200 ft.) in length. Each circuit has two spans that are 183 m (600 ft.) in length. The line is configured in a loop by connecting the two circuits at one end, providing a total of 732 m (2400 ft.) of transmission conductor with which to perform tests.

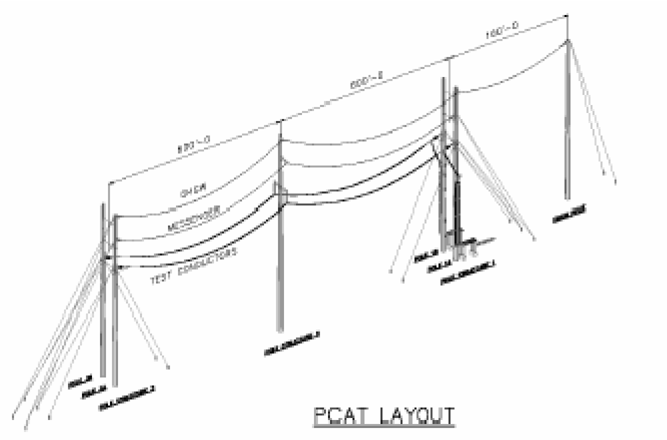

Figure 2. PCAT design layout showing the pole structures and supports.

A thermocouple instrumentation system was used to measure conductor temperatures along the length of the line. The conductor surface temperatures used in this analysis were measured at locations 7,6 m (25 ft.) from either dead-end, ¼ span, mid-span and ¾ span in each of the two span lengths. Core temperatures were taken at the mid-point of each span. A CAT-1 system operating in continuous sampling mode was used to collect tension, net radiation and ambient temperature, wind speed and direction. Data was collected from all sensors along the test line at 1-minute intervals during temperature cycling.

Data used for this analysis was collected on February 27th, 2004. The test line at that time was configured with a 675 kcmil trapezoidal ACCR (aluminum-conductor composite-reinforced) conductor which had undergone 99 hours and 16 cycles of high temperature testing.

High Temperature Test, February 27, 2004.

This test run was selected because the conductor had already undergone several test runs and its behavior had stabilized. The data from this 6,5 hour high temperature test does not differ substantially from any other tests runs made before or after the test. The dc current was modulated between 1215 and 1671 Adc with an average of 1470 Adc in order to maintain an approximate average conductor temperature rise of 180°C

During this test the ambient temperature averaged 6°C and the solar temperature 10°C. The record of the individual thermocouple temperatures is shown in Figures 3 and 4. The standard deviations of the individual simultaneous conductor temperatures were 23°C in Figure 3 and 27°C in Figure 4, which is +/- 15%. For each minute, the standard deviation of the conductor temperatures was calculated and then these were averaged over the test period. These standard deviations characterize the systematic variation.

This report does <u>not</u> analyze the dependence of conductor temperature on the weather variables. Such analysis is presented in [3] which concluded that the measured conductor temperatures were relatively close to those predicted by IEEE 738 standard and the measured weather parameters and line current.

The temperature data shows that the conductor temperatures were generally higher at midspan. This could be anticipated because at maximum conductor temperatures the midspan clearance of the conductor was 7,0-7,3 m (23-24 ft.) from ground, compared to 12,5-12,8 m (41-42 ft.) from the ground at the thermocouples nearest to the ends of the span. Such a height difference can cause a substantial difference in the wind velocity. Because of the relatively small diameter of the compact conductor, the core temperatures were typically only 3-4^{o}C higher than surface temperatures.

The comparison between "treeside" and "roadside" circuits shows significant temperature differences from time to time. A comparison between average temperatures is shown Figure 5. The difference is most likely caused by the difference in wind speeds on different sides of the narrow line corridor. The conductor temperatures indicate that the average effective wind speed around noon was slightly below 0,6 m/s on the "treeside" and about 0,8 m/s on the "roadside" span. Comparison to the measured wind speed at 12:00 Noon (1,77 m/s (5.8 ft/sec) at 24 degrees angle) would imply a conductor temperature of 152^{o}C. This compares reasonably well with the measured average temperatures of 176^{o}C and 165^{o}C for tree and road side spans respectively. Earlier and later tests indicate similar relative variations (also in the opposite direction) between the two sides of the test line.

The conductor temperature showed a span wise trend of higher temperatures in the middle of the span than at the ends of the span, as shown in Figure 6.

The calibrated relationship between the conductor tension measurements and the average temperature are shown in the calibration curves of Figures 7 and 8. Note that the measured tension/temperature relationship shows a certain amount of hysteresis. This can be explained by a combination of two processes:

1. The knee point of a layered conductor is actually a range of temperatures. The knee point of the 675 kcmil ACCR conductor falls between 95-110^{o}C. Manufacturing tolerances make it impossible for all the wires in the outside layers to reach zero tensile stress simultaneously. When passing through the knee point range, each strand must settle in relationship to the others.
2. There is substantial longitudinal variability in the conductor temperature. This means that there are compressive and tensile stresses in the outside layers which will try to move the outside wires longitudinally. Such stresses are constrained by the friction between the core and the outside layers.

As a result, the tension-temperature equilibrium shown in Figures 6 and 7 will exhibit a clear, albeit minor, hysteretic behavior.

Figures 9 and 10 show the relationship between the measured average temperature of the two circuits and the conductor temperatures derived based on tension measurements. The close correlation between the measurements proves conclusively that the conductor tension is a function of the average temperature of the line section.

Conclusions:

1. During the test, the average temperature rise was about 180^{o}C as compared to solar temperature, and the longitudinal variation of individual temperature rises along the two spans was +/-40^{o}C, i.e. about 22%.

2. The 22% variation is approximately one half systematic variations (some locations show, on the average, higher temperatures than others) and approximately one half random variations.

3. Because the temperature rise tends to be highest at locations with the lowest clearance to ground, conductor rating measurements should be based on temperatures at such locations, unless other locations are more sheltered from wind.

4. Conductor tension follows quite accurately the average temperatures of the line sections.

5. When conductor temperature excursions exceed the kneepoint temperature, tension/temperature relationship indicates a moderate hysteresis.

Acknowledgement

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The Power-line Conductor Accelerated Test Facility is operated by Oak Ridge National Laboratory for the U.S. Department of Energy, Office of Electric Transmission and Distribution. The Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the U.S. Department of Energy under contract no. DE-AC05-00OR22725.

References

[1] ORNL Reporter, No 40, August 2002

[2] http://www.ornl.gov/sci/oetd/about.htm

[3] "Weather Observation and Thermal Ratings in a Short, High Temperature Test Line", Herve Deve, 3M. Presented at the IEEE TP&C Panel on Selection of Weather Parameters for Overhead Lines, Denver 2004.

Figure 3. Thermocouple Temperatures- Tree Side
February 27, 2004

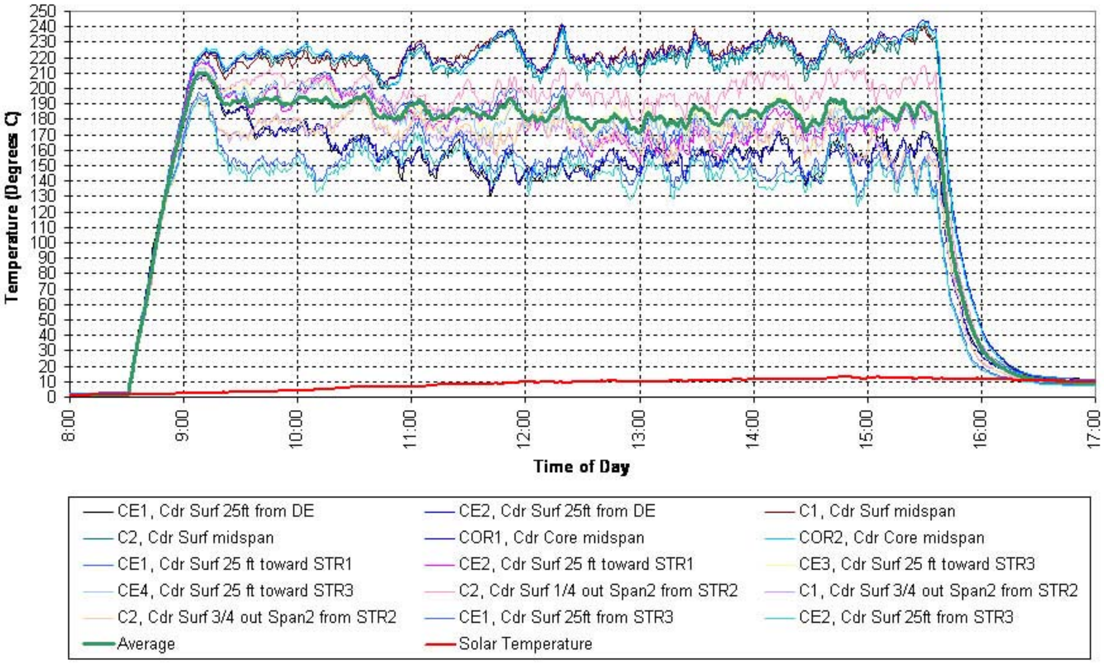


Figure 4. Thermocouple Temperatures- Road Side
February 27, 2004

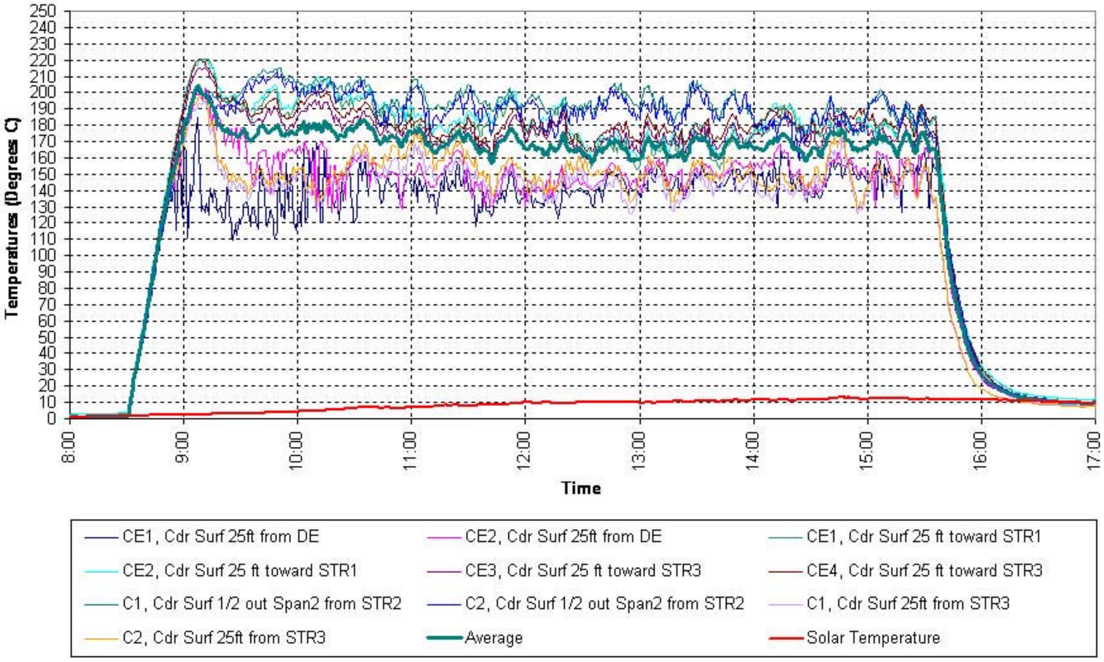


Figure 5. Average Temperatures of Road and Tree Sides
February 27, 2004

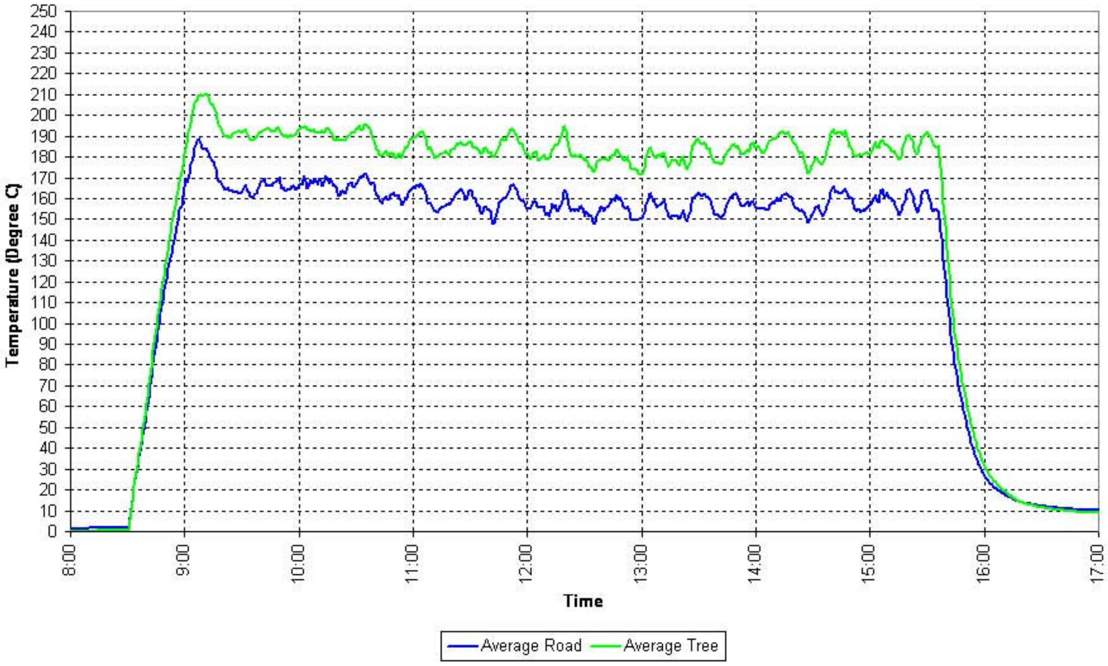


Figure 6. Variation of average temperature rise along the line

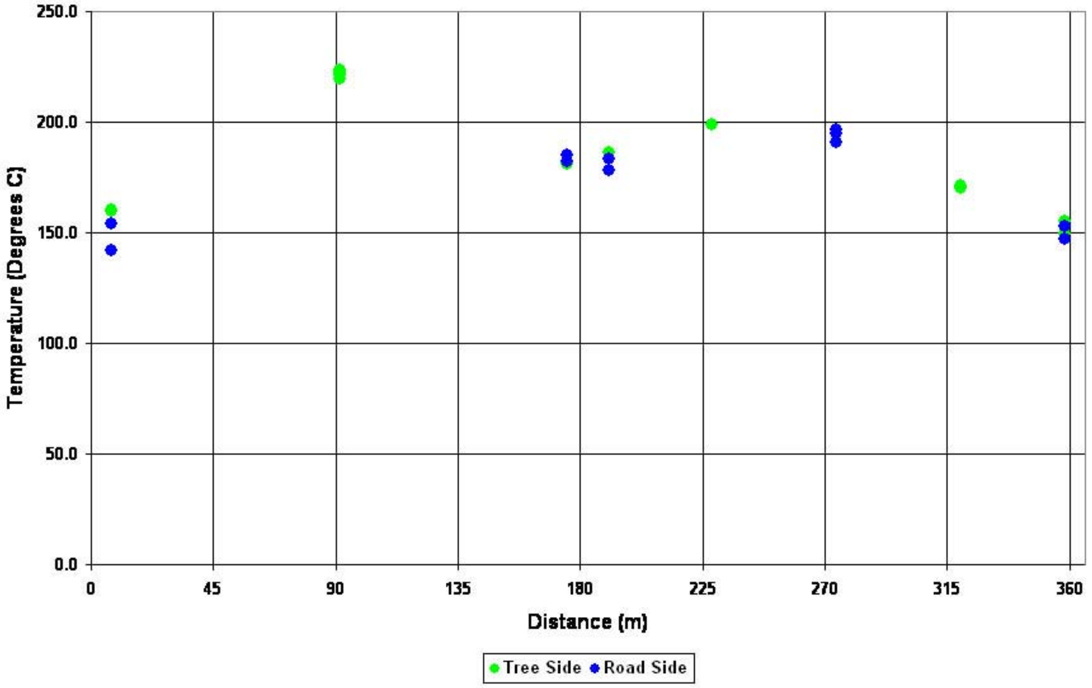


Figure 7. Tree Side Conductor Temperature Calibration Curve

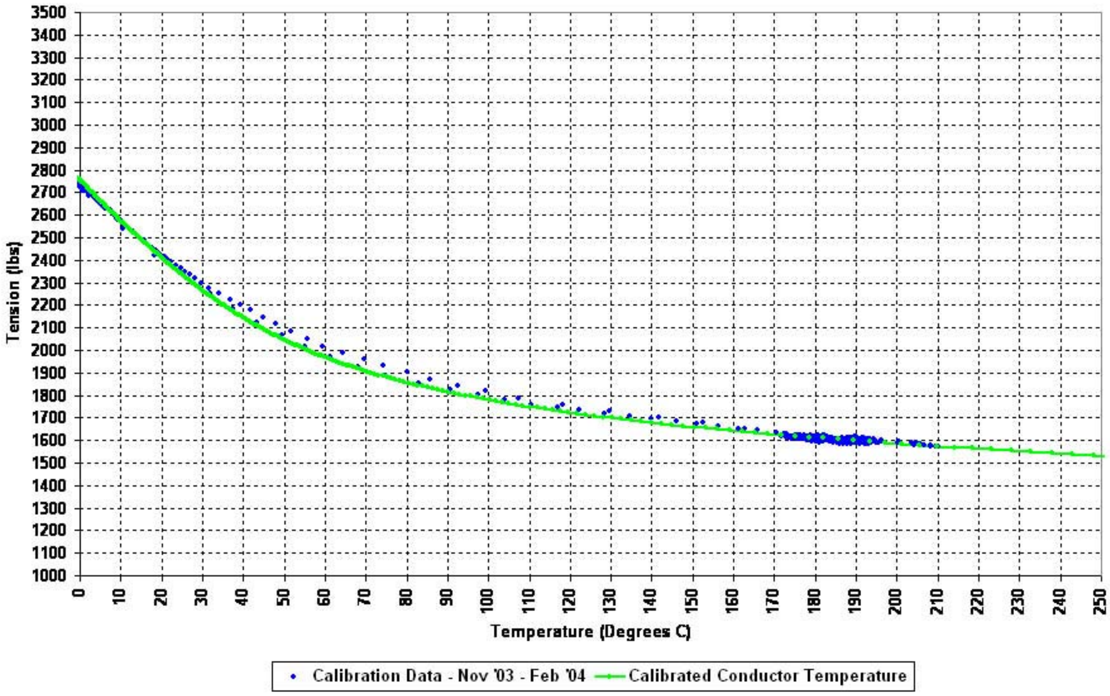


Figure 8. Road Side Conductor Temperature Calibration Curve

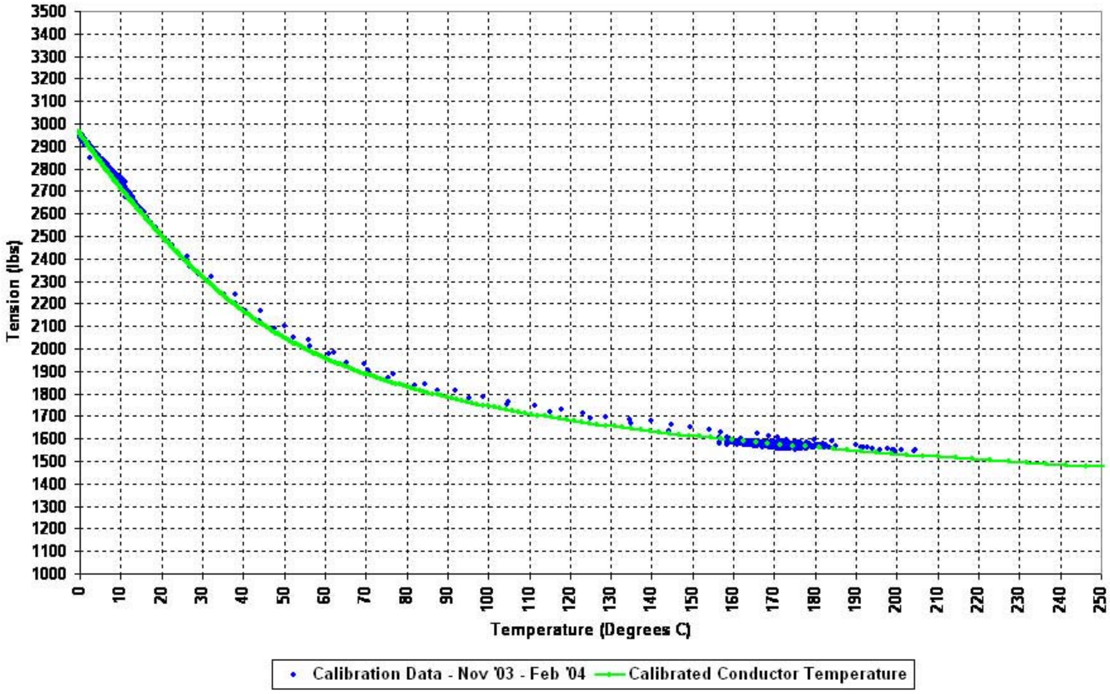


Figure 9. Conductor Temperature Comparison
Tree Side (Port 1) - 2/27/04

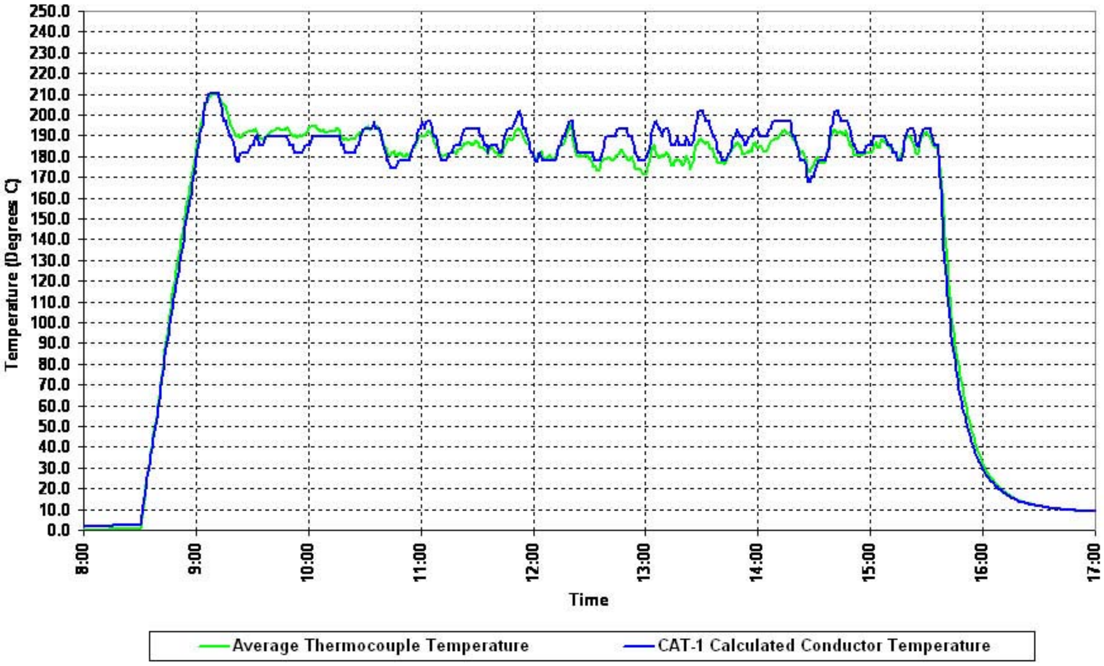
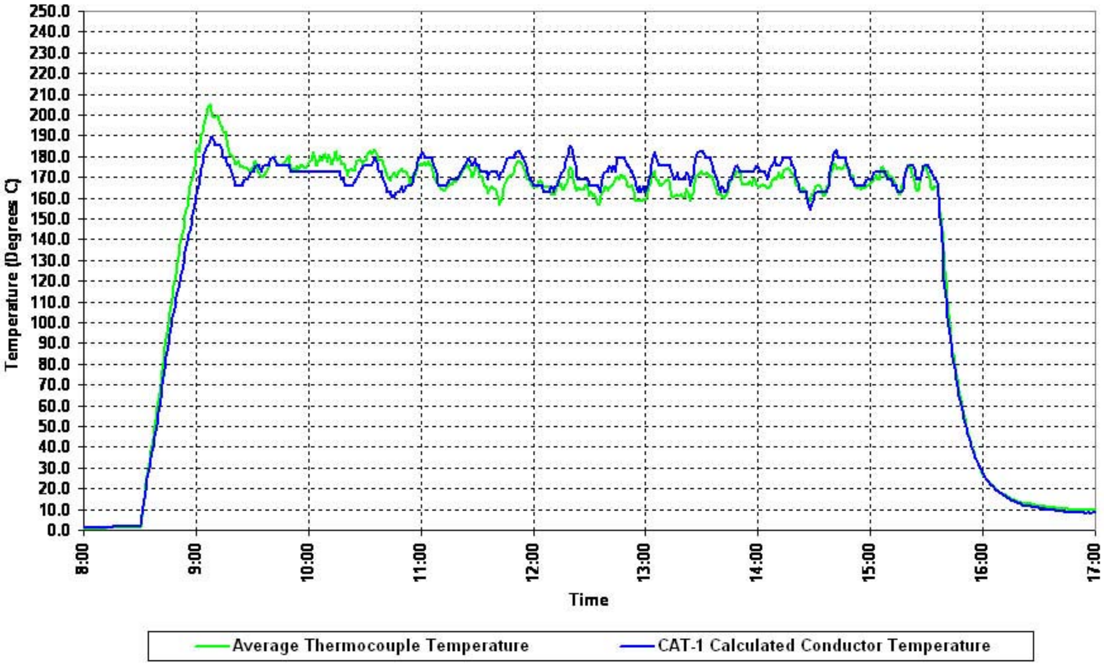


Figure 10. Conductor Temperature Comparison
Road Side (Port 2)- 2/27/04



Appendix C.1

DOE Peer Review Presentation – May 20, 2002

Aluminum Composite Conductor Tests for the 3M Company

U.S. Department of Energy
Transmission Reliability Program
Peer Review

John P. Stovall

Oak Ridge National Laboratory

Doubletree Hotel Crystal City
Arlington, VA
May 20, 2002

ORNL Project Team
D. Tom Rizy
Roger A. Kisner
John P. Stovall

Brendan J. Kirby
Charles Bruce
Lynn Degenhardt
Randall Wetherington

ORNL Project Summary

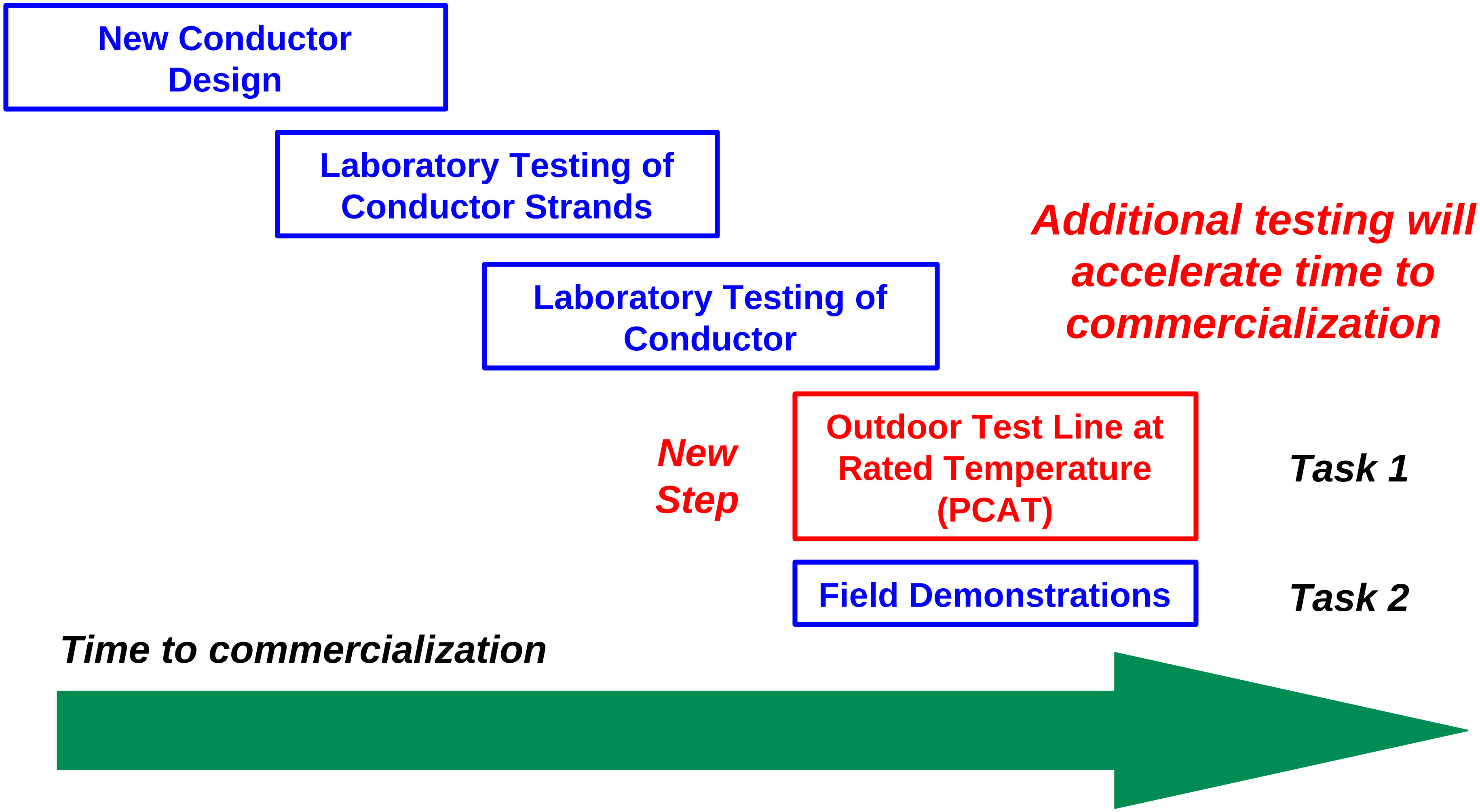
Aluminum Composite Conductor Tests for the 3M Company

- **New Project, start date March 25, 2002**
- **FY 2002 Budget – $620,000**
- **Duration – 3 years**
- **Goal**
  - **To accelerate the commercial acceptance of the aluminum composite conductor**
- **Objective**
  - **To verify the aluminum composite conductor and accessory performance by providing performance data based upon field testing including through testing at rated conductor temperatures**

ORNL CRADA with 3M Company

- **Project Plan (ORNL CRADA Tasks)**
  - **Task 1 – Thermal Cycling Conductor Tests**
    - **ORNL to build outdoor test facility, install conductor, test at high-current / low-voltage / rated conductor temperature of 210°C for approximately 500 thermal cycles**
    - **Facility name is "PCAT" - Powerline Conductor Accelerated Test**
    - **Will measure sag, tension, current and conductor temperature to quantify conductor performance**
    - **Will test 3 conductor sizes – 477, 795 and 1272 kcmil ACCR**
  - **Task 2 – Measurement and Analysis for Conductor Field Tests**
    - **3M to select several utility field test sites and install conductor with host utilities**
    - **ORNL to provide monitoring hardware as necessary, collect and analyze field data**

Bringing a New Conductor to Market



New Conductor Design

Laboratory Testing of Conductor Strands

Laboratory Testing of Conductor

Additional testing will accelerate time to commercialization

New Step

Outdoor Test Line at Rated Temperature (PCAT)

Task 1

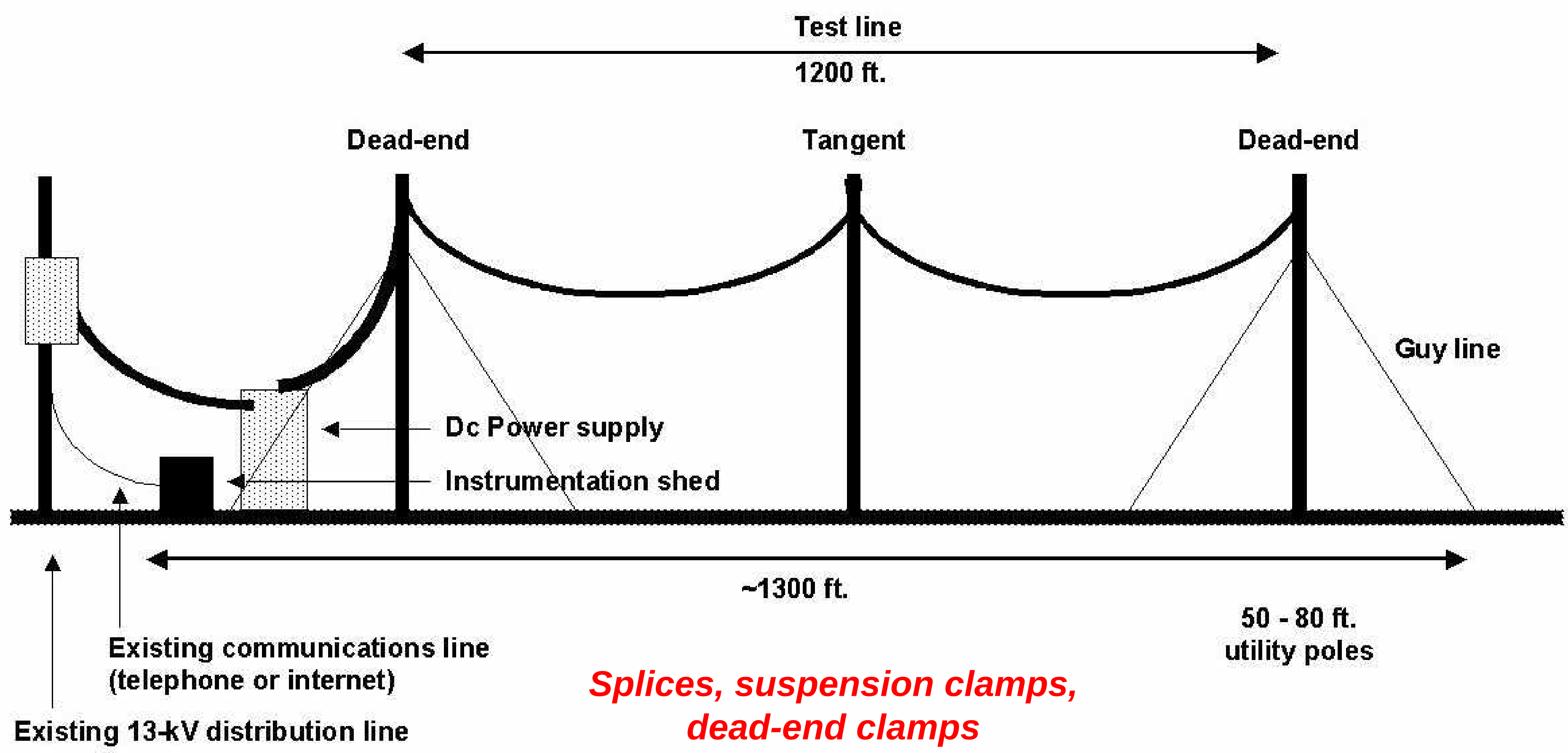
Field Demonstrations

Task 2

Time to commercialization

PCAT - Profile View of Outdoor Test Line

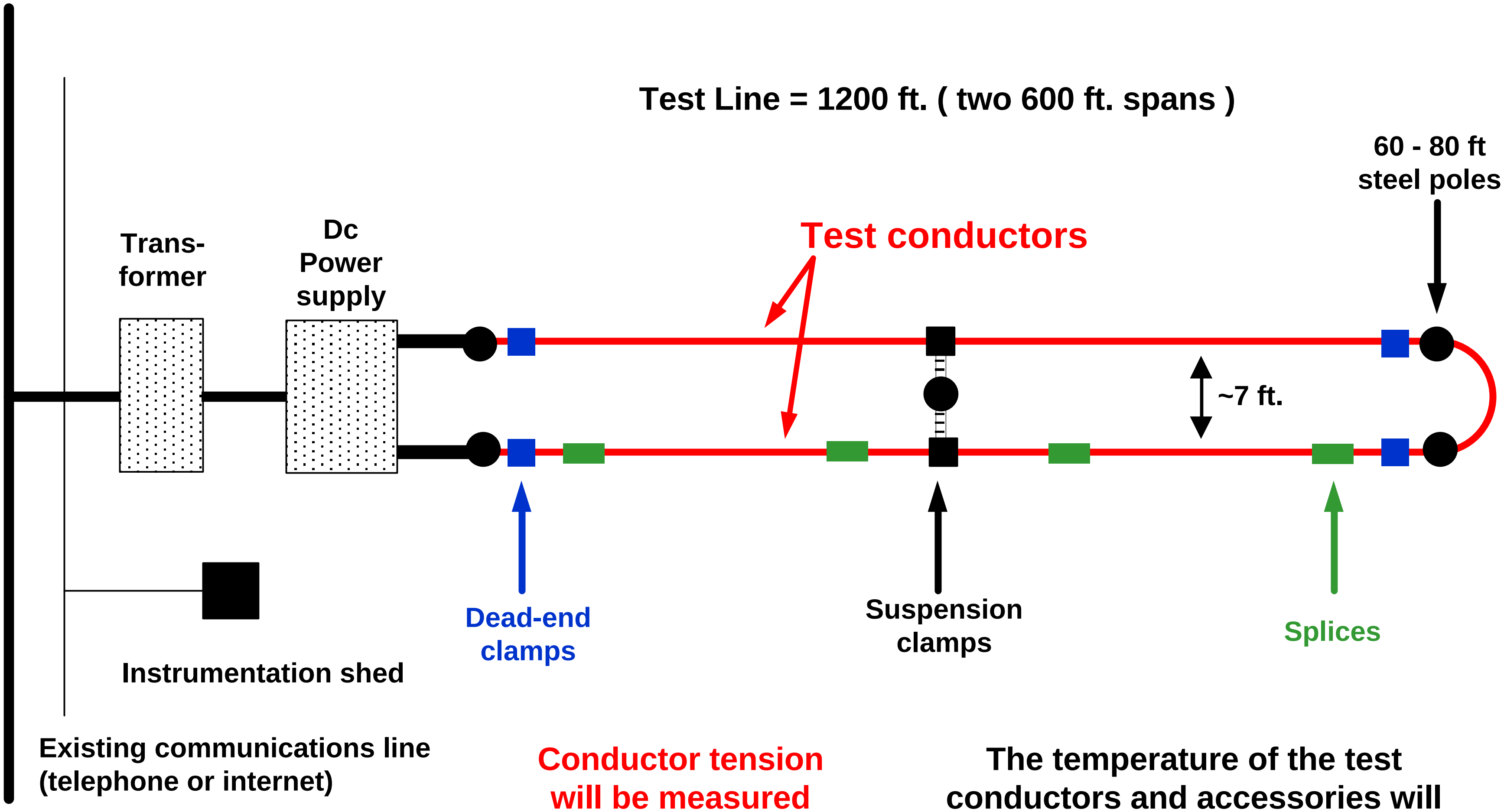
- **Test of conductor and accessories**



Splices, suspension clamps, dead-end clamps

Task 1

PCAT - Plan View of Outdoor Test Line



Test Line = 1200 ft. (two 600 ft. spans)

60 - 80 ft steel poles

Test conductors

Trans- former

Dc Power supply

~7 ft.

Dead-end clamps

Suspension clamps

Splices

Instrumentation shed

Existing communications line (telephone or internet)

Existing 13.8-kV distribution line

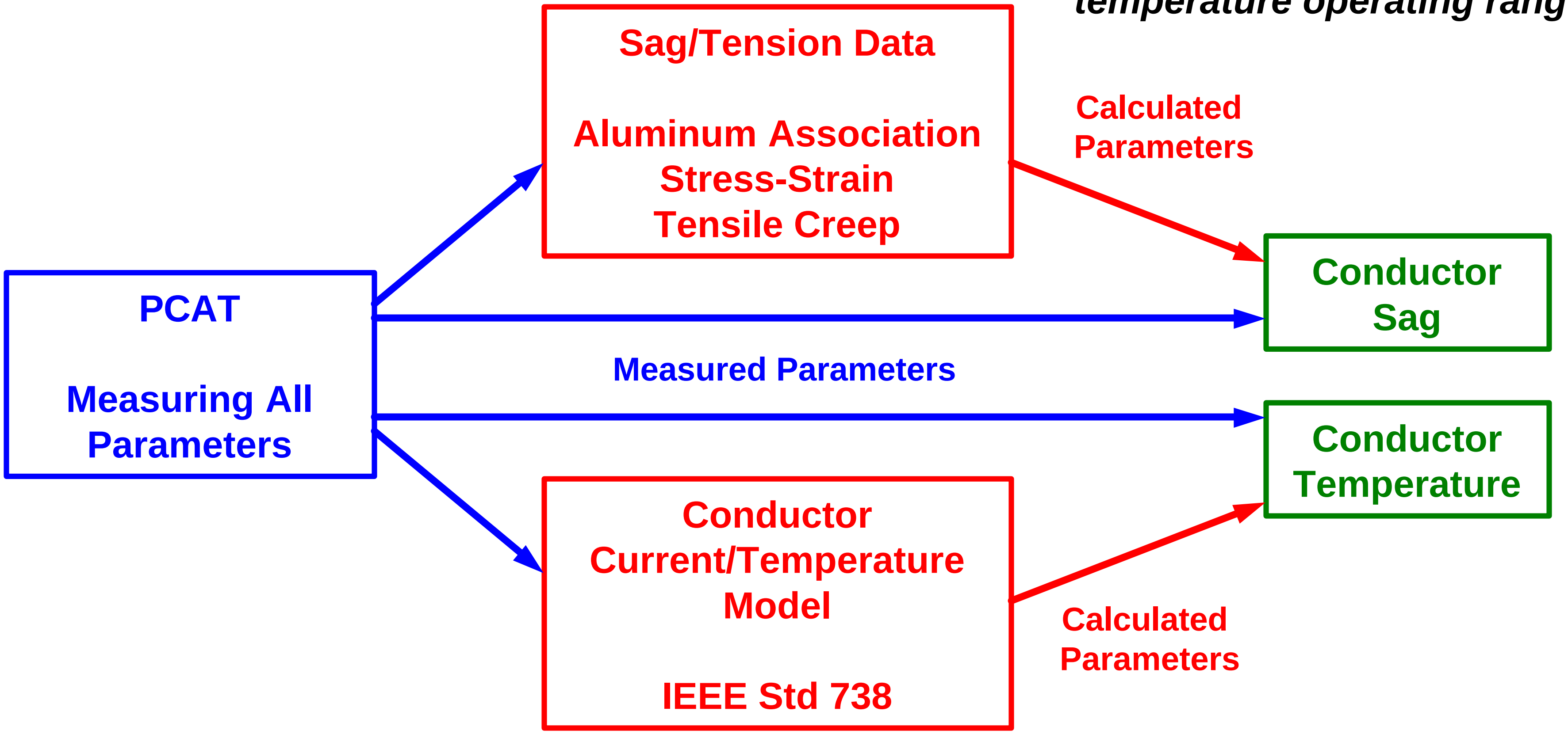
Conductor tension will be measured using a CAT-1 system

The temperature of the test conductors and accessories will measured using thermocouples

Task 1

PCAT - Thermal Cycling Will Verify New Conductor Performance and Existing Models

Verification over entire temperature operating range



PCAT

Measuring All Parameters

Sag/Tension Data

Aluminum Association Stress-Strain Tensile Creep

Conductor Current/Temperature Model

IEEE Std 738

Measured Parameters

Calculated Parameters

Calculated Parameters

Conductor Sag

Conductor Temperature

PCAT - Equipment needed for Outdoor Test Line

- dc power supply
  - Electronics van to house dc power supply
- Standard transformer
  - 2.5 MVA, 13.8-kV / 4160V
- Line structures
  - Five standard utility steel poles, guys, shield wires, etc.
- Instrumentation
  - CAT-1 (tension), thermocouples, weather station, cable height meter
  - Enclosure for instrumentation ~ 10 ft. X 12 ft.

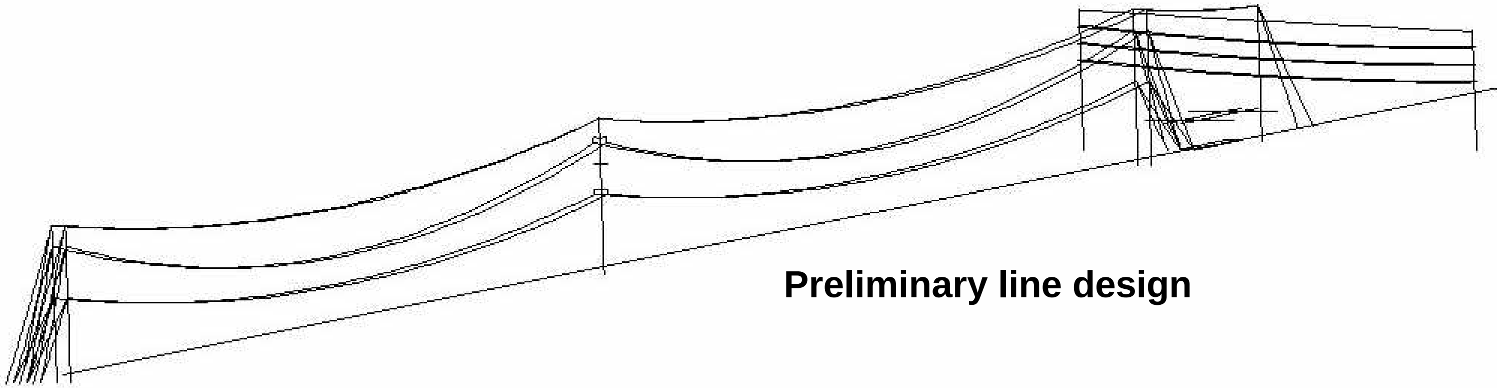
Surplus dc Power Supply Acquired
600 Vdc, 3500 A or 400 Vdc, 5000 A

Transrex Model ISR 2294

Task 1

TVA Providing Line Structure Design

- TVA will perform the line structure design
  - Key design issue is horizontal deflection of the steel poles
  - PLS-CADD (Power Line Systems - Computer Aided Design and Drafting) being used
- ORNL will purchase purchase line structure materials and hardware from TVA
- Combination of TVA and ORNL Utility Services will install test line



Preliminary line design

Task 1 Project Schedule

Task	Apr 02	May 02	Jun 02	Jul 02	Aug 02	Sep 02	Oct 02	Nov 02	Dec 02
1.Design/Construct Test Facility									
1. a Power equipment	■	■	■						
1. b Instrumentation system	■	■	■						
2. Install 477 conductor				■					
3. Test 477 conductor					■	■	■	■	■
4. Analyze and evaluate tests					■	■	■	■	■

Evaluation Guidelines

- **Project Performance**
  - **The CRADA between 3M Company and ORNL has formalized and documented the management system; and the planning and coordination of accomplishments and future plans. The CRADA has established the public/private partnership, cost-sharing and technology transfer mechanism. In addition, ORNL has sought the assistance of TVA in the design and construction of the outdoor test line.**
- **Project Value**
  - **Project contributes directly to the following goal:**
  - **Department of Energy's FY 2002 Budget Request to Congress - "Power System Reliability will develop advanced transmission technologies that promote competitive markets, ensure system reliability, increase network capacity for large scale, long distance power transfers, and …"**

Appendix C.2

DOE Peer Review Presentation – January 29, 2004

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National Transmission Technology Research Center

U.S. Department of Energy Transmission Reliability Program Peer Review

John P. Stovall

Oak Ridge National Laboratory

ORNL Project Team
D. Tom Rizy
Roger A. Kisner
John P. Stovall

Marriott at Metro Center
775 12th Street, N.W.
Washington, D.C. 20005

January 29, 2004

National Transmission Grid Study

One of the 51 Recommendations

“DOE will develop national transmission-technology testing facilities that encourage partnering with industry to demonstrate advanced technologies in controlled environments.

Working with TVA, DOE will create an industry cost-shared transmission line testing center at DOE ’s Oak Ridge National Laboratory (with at least a 50 percent industry cost share).*”

*National Transmission Grid Study, U.S. DOE, May 2002 www.ntgs.doe.gov

National Transmission Technology Research Center

T1

Outdoor PCAT

Powerline Conductor Accelerated Test Facility

T2

Indoor PCAT

Powerline Conductor Accelerated Test Facility

T3

PCOT (TVA lines)

Powerline Conductor Operational Test Facility

T4

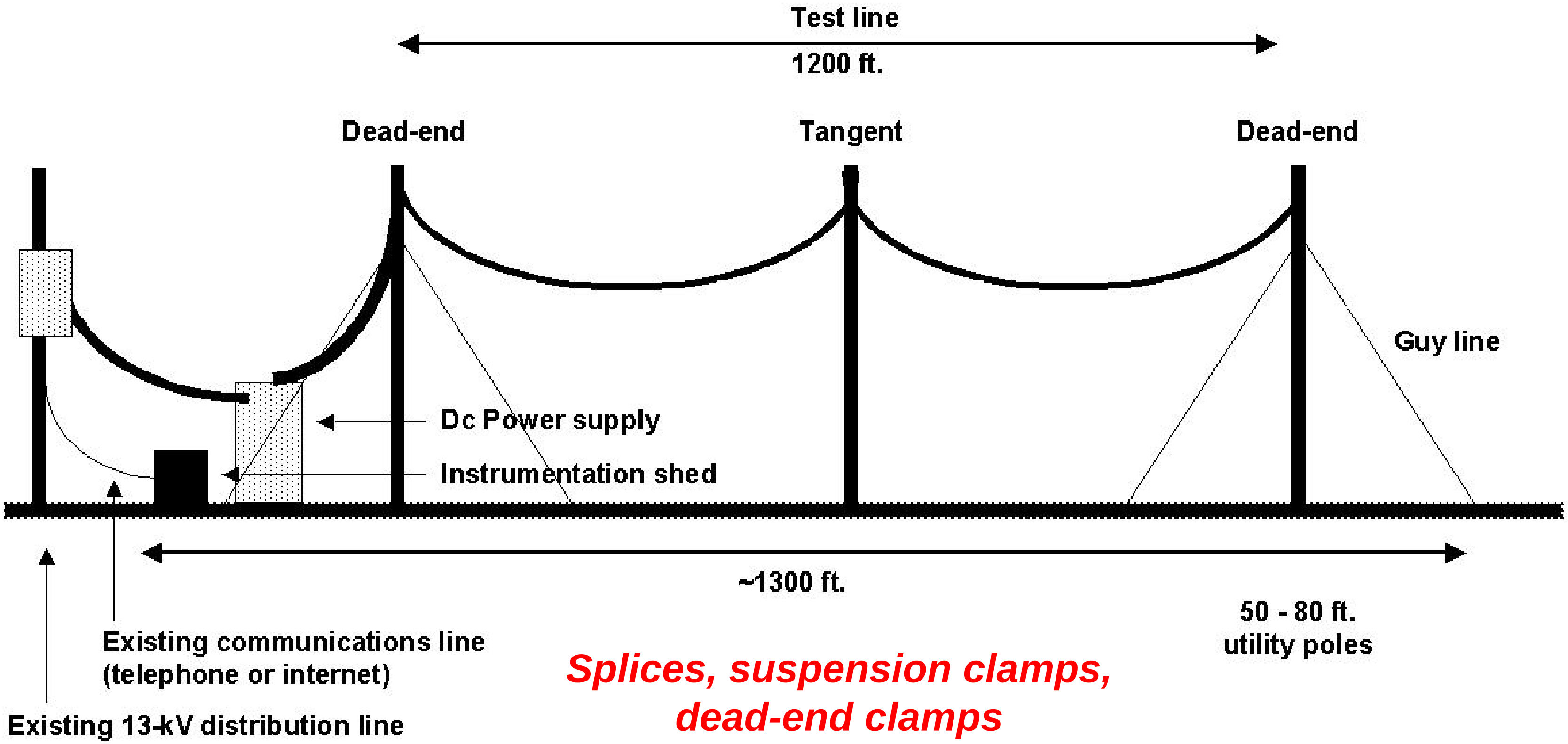
TPET (Substation)

Transmission Power Electronics Test Facility

T1. PCAT - Profile View of Outdoor Test Line

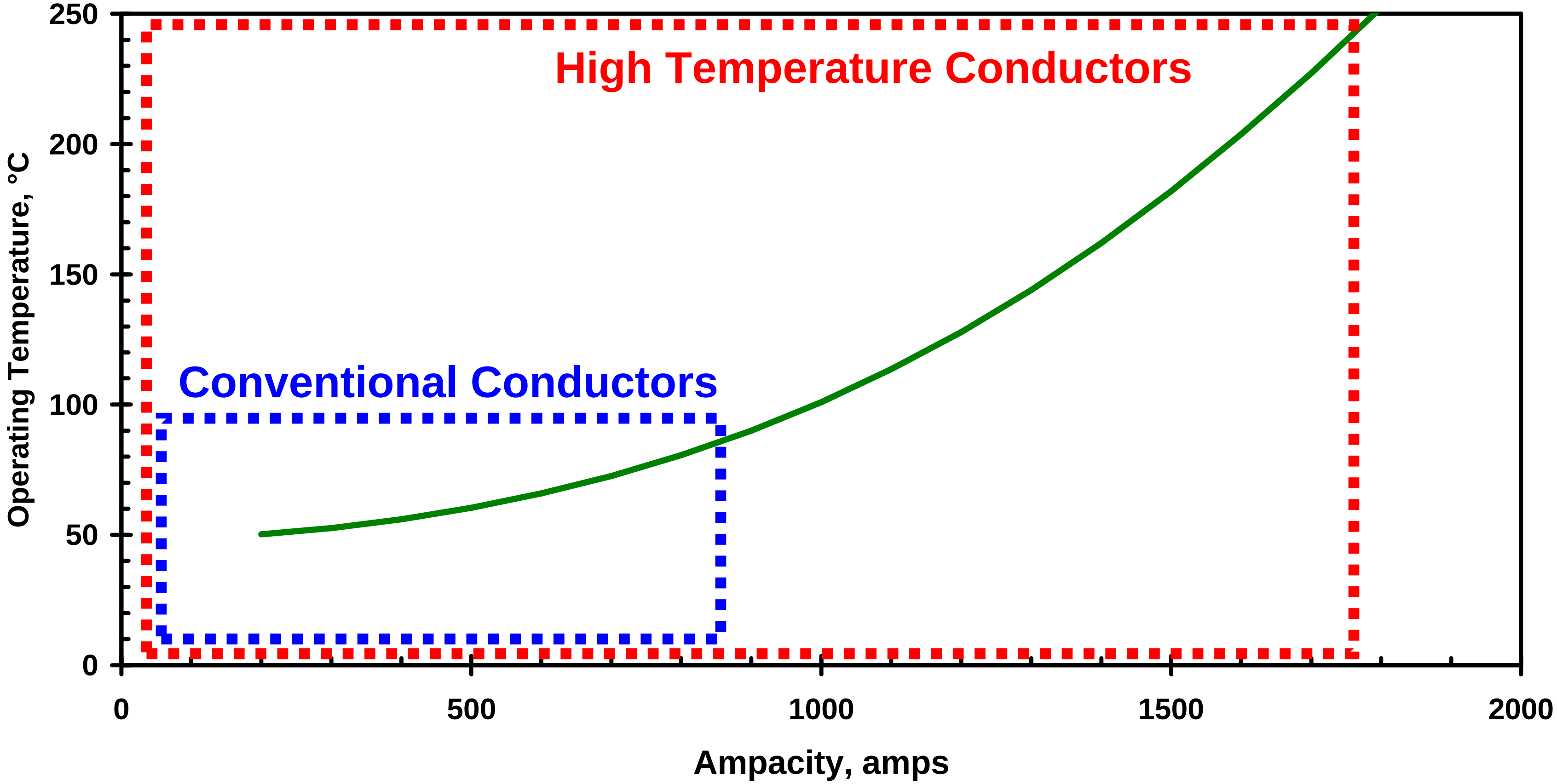
PCAT - Powerline Conductor Accelerated Test

Initial Concept for Test Facility
Developed with 3M Company



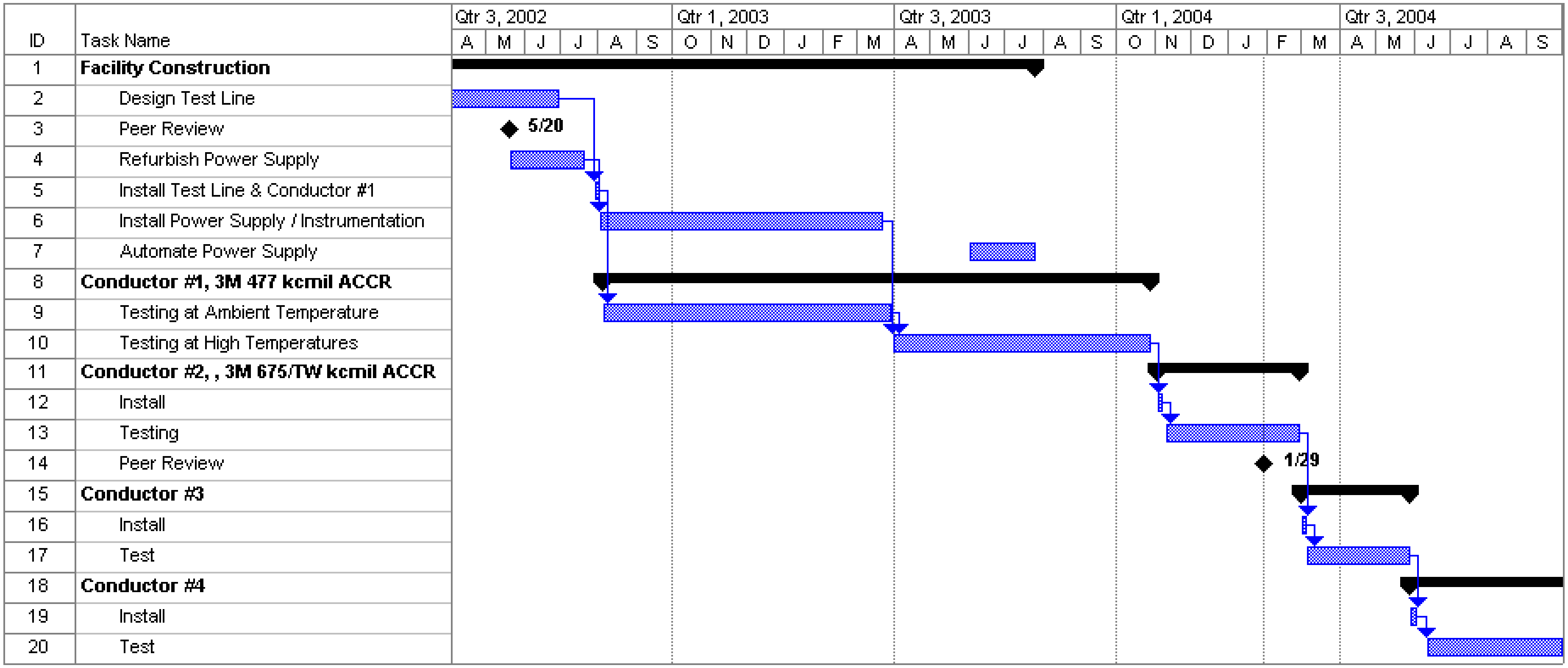
Splices, suspension clamps, dead-end clamps

T1. PCAT - Benefit of Advanced Transmission Line Conductors



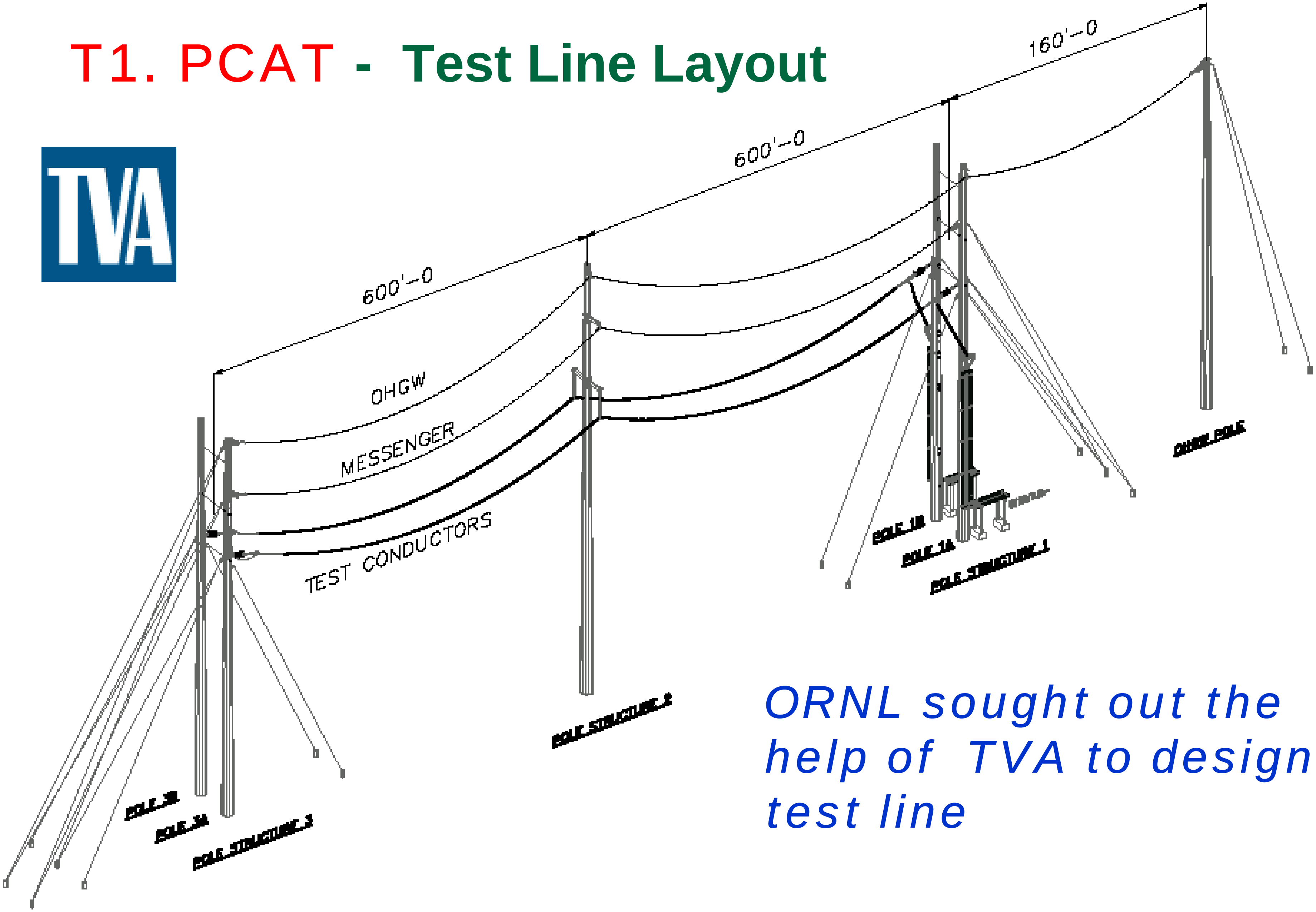
Need to test / verify new conductors over entire operating range

T1. PCAT - Project Schedule



ID	Task Name
1	**Facility Construction**
2	Design Test Line
3	Peer Review
4	Refurbish Power Supply
5	Install Test Line & Conductor #1
6	Install Power Supply / Instrumentation
7	Automate Power Supply
8	**Conductor #1, 3M 477 kcmil ACCR**
9	Testing at Ambient Temperature
10	Testing at High Temperatures
11	**Conductor #2, , 3M 675/TW kcmil ACCR**
12	Install
13	Testing
14	Peer Review
15	**Conductor #3**
16	Install
17	Test
18	**Conductor #4**
19	Install
20	Test

T1. PCAT - Test Line Layout



ORNL sought out the help of TVA to design test line

T1. PCAT - TVA Constructed the Test Line and Installed the First 3M Test Conductor in July 2002

TVA

T1. PCAT – A surplus power supply was refurbished and tested in June / July 2002

T1. PCAT - Line Structures and Test Hardware

Structure #1, Dead-end

Structure #2, Suspension

Structure #3, Dead-end

Structure #0, Fiberglass Pole

STRONGWELL

- **Two 600 ft. spans with 2400 ft. of test conductor**
- **Four dead-end clamps**
- **Two suspension clamps**
- **Two splices**
- **Conductor clamps**
- **Jumpers and terminal pads**

T1. PCAT - Transmission Structures

Structure #1 and #3 are dead-ends

Structure #2, Suspension

T1. PCAT - CAT-1 Transmission Line Monitoring System

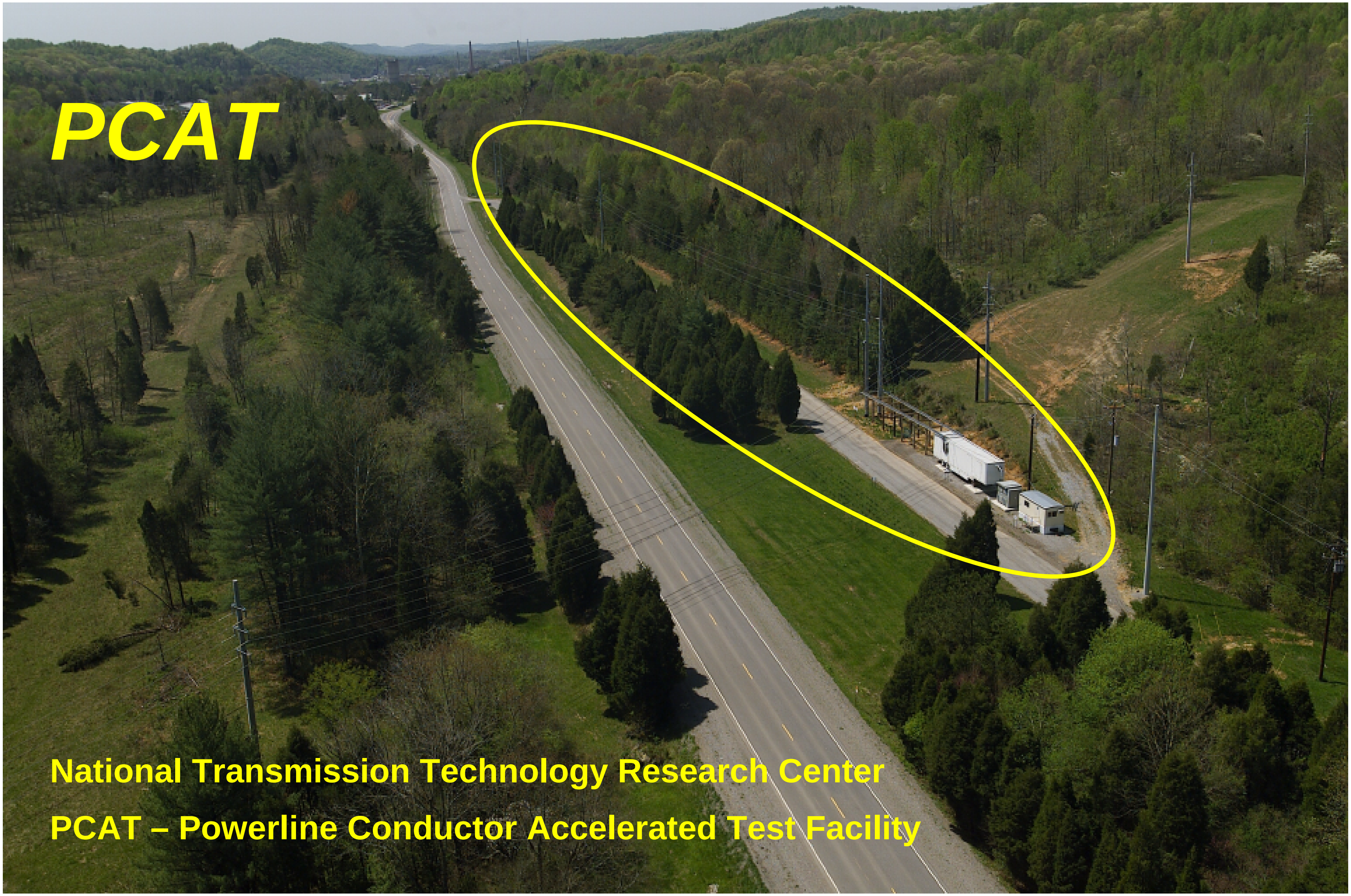
Load cells measuring conductor temperature

Wind Speed and direction

Net Radiation Sensor measuring combination of ambient, wind speed, wind direction and solar radiation on conductor equivalent

Electronics, solar panel, and ambient temperature

PCAT

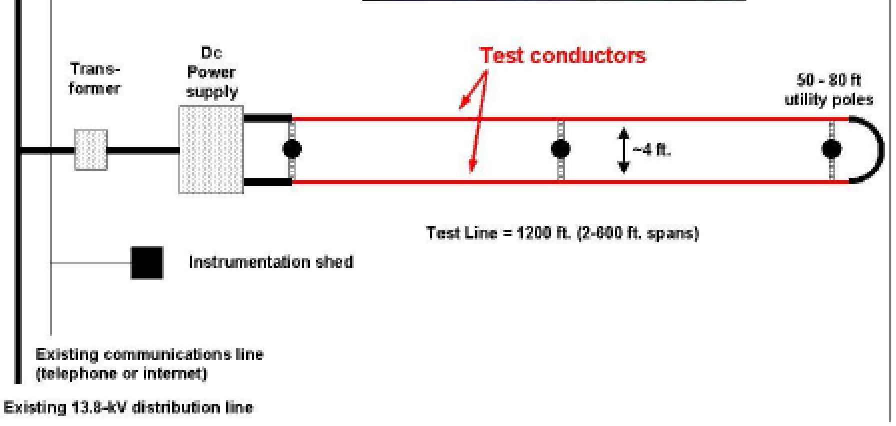


National Transmission Technology Research Center

PCAT – Powerline Conductor Accelerated Test Facility

T1. PCAT – Facility Capabilities

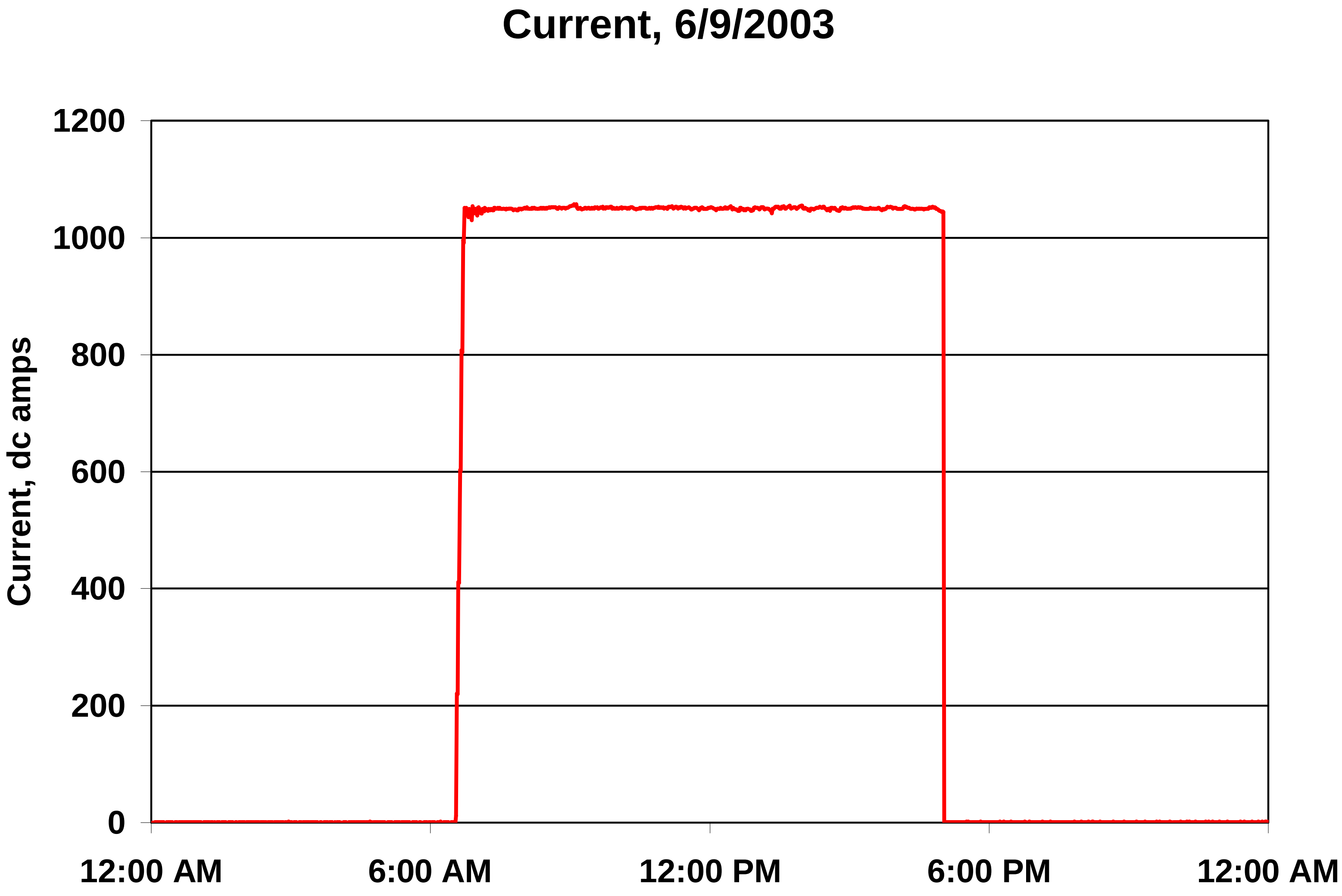
- **Powerline Conductor Accelerated Testing**
  - ➢ Accelerated life-cycle testing
  - ➢ Initially will test new 3M conductors
  - ➢ Will test other new conductor designs and existing conductors
- **Thermal Cycle Testing**
  - Controlled testing
  - Conductor and accessories
  - Up to 300°C
- **Capabilities**
  - 2400 feet of conductor
  - 2 – 600 foot spans
  - Low Voltage, 0 to 400 Vdc
  - High Current, up to 5,000 Adc



T1. PCAT - Measurements

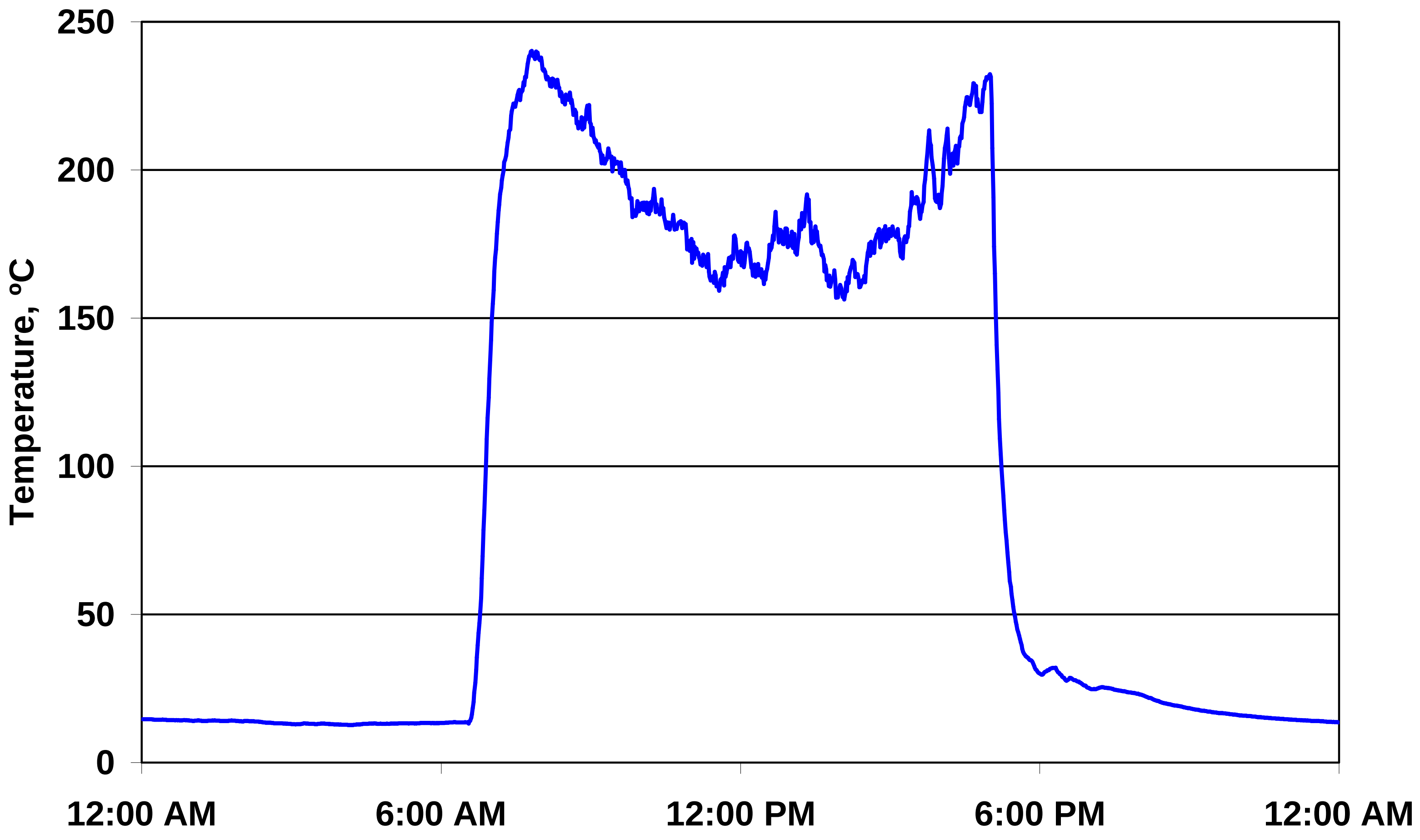
- Conductor/accessory temperature
  - Direct contact on surface or conductor core
  - 128 thermocouples available
  - 40 to 80 thermocouples used for testing
- Applied current and voltage
  - Measured by power supply
- Conductor sag
  - Laser at mid-span #1 on tree side circuit
- Conductor tension
  - Load cells on both circuits
- Weather
  - Ambient temperature, wind speed, wind direction
  - Conductor net radiation sensor
- PC-based data acquisition system
  - 10 second polling
  - 1 minute data archive

T1. PCAT – Constant Current Test

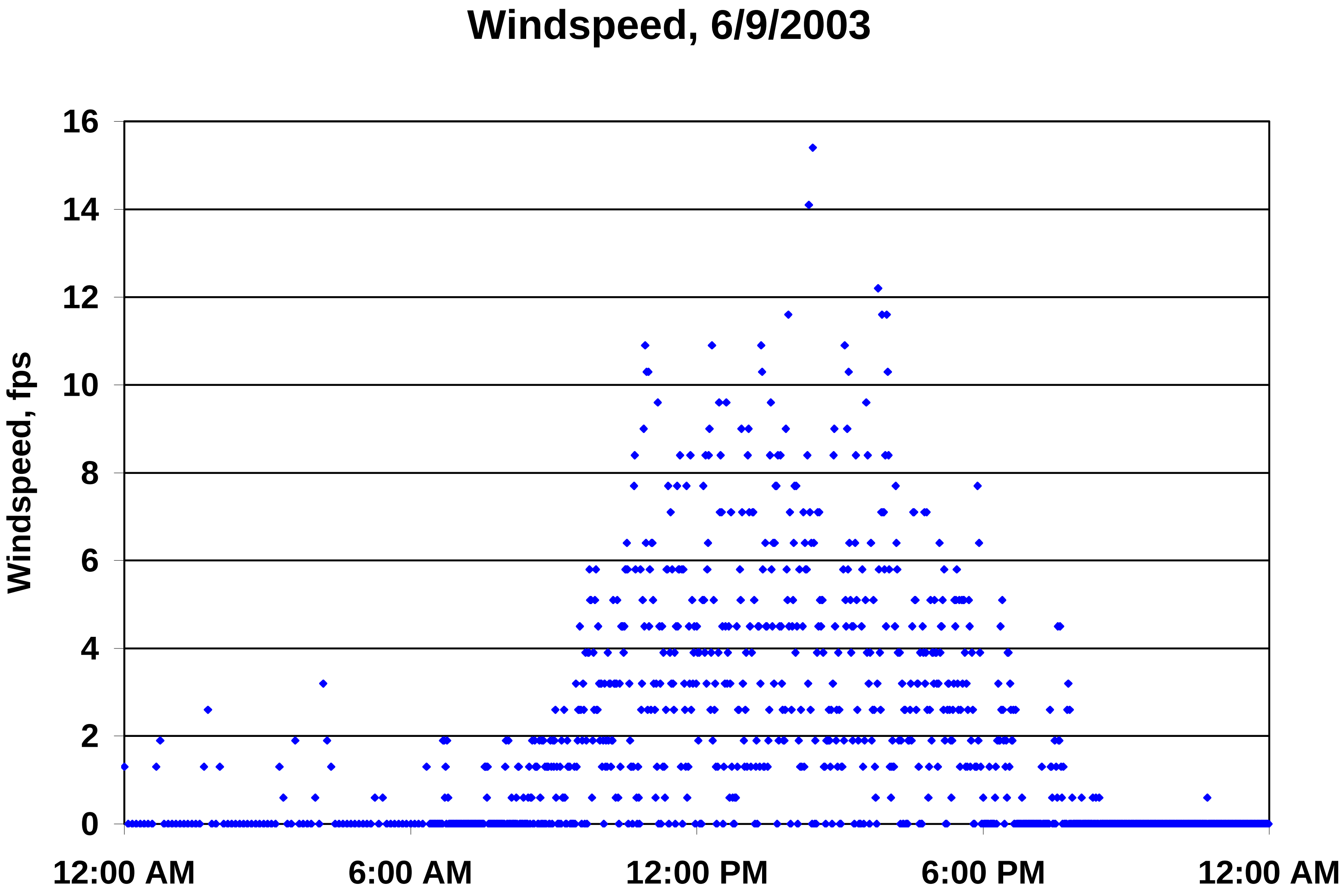


T1. PCAT – Constant Current Test

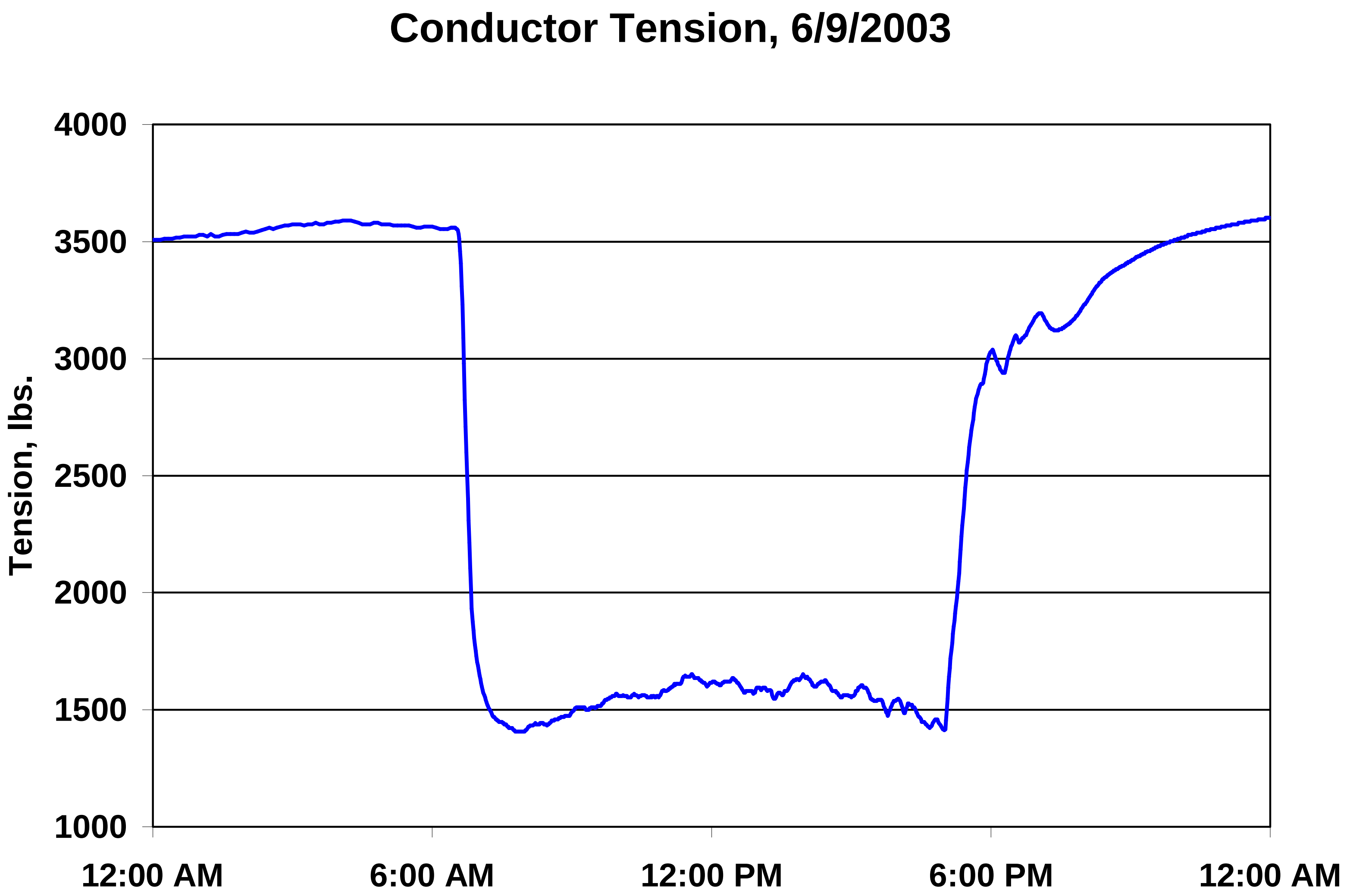
Average Conductor Temperature, 6/9/2003



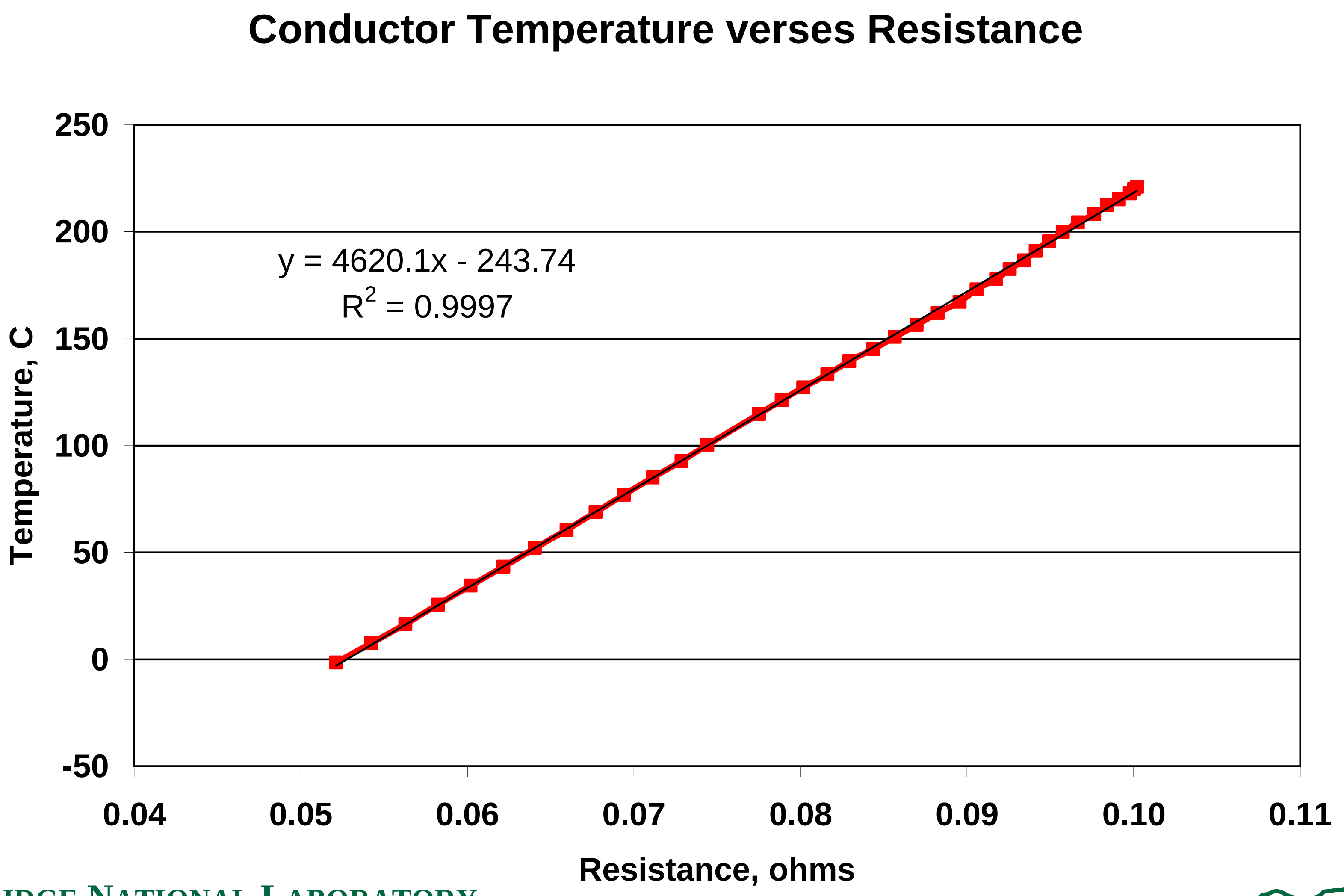
T1. PCAT – Constant Current Test



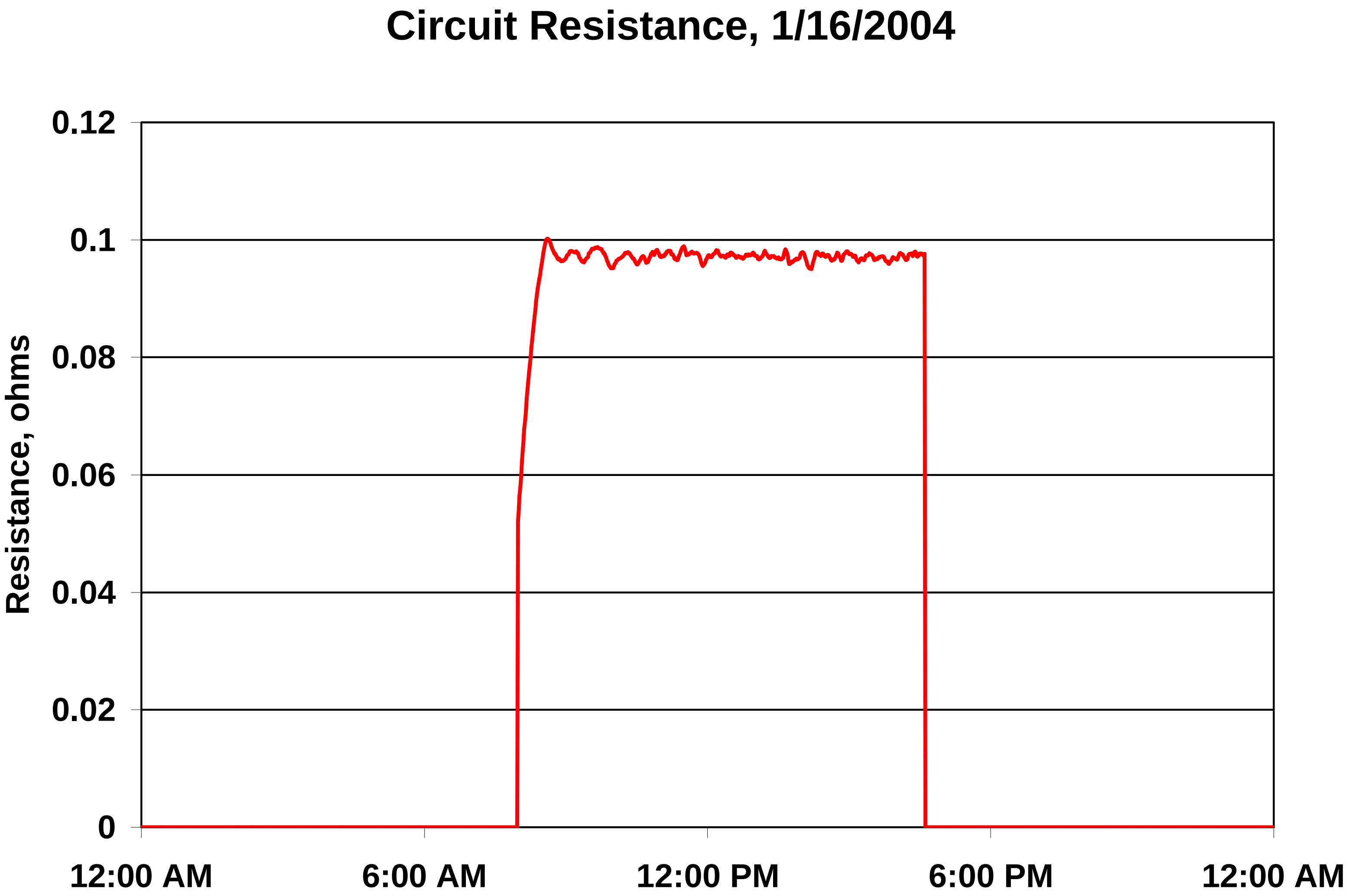
T1. PCAT – Constant Current Test



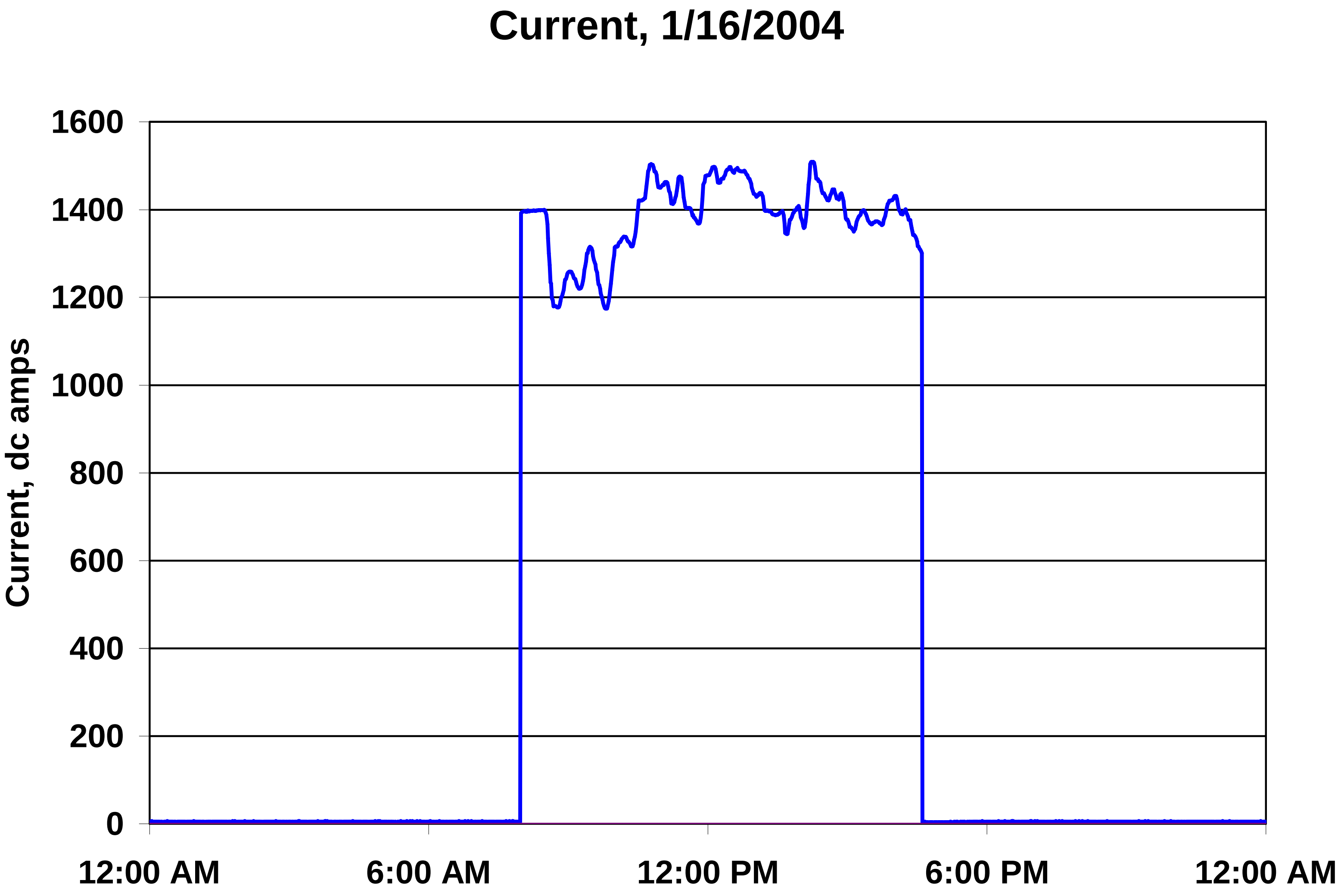
T1. PCAT – Constant <u>Temperature</u> Test



T1. PCAT – Constant Temperature Test

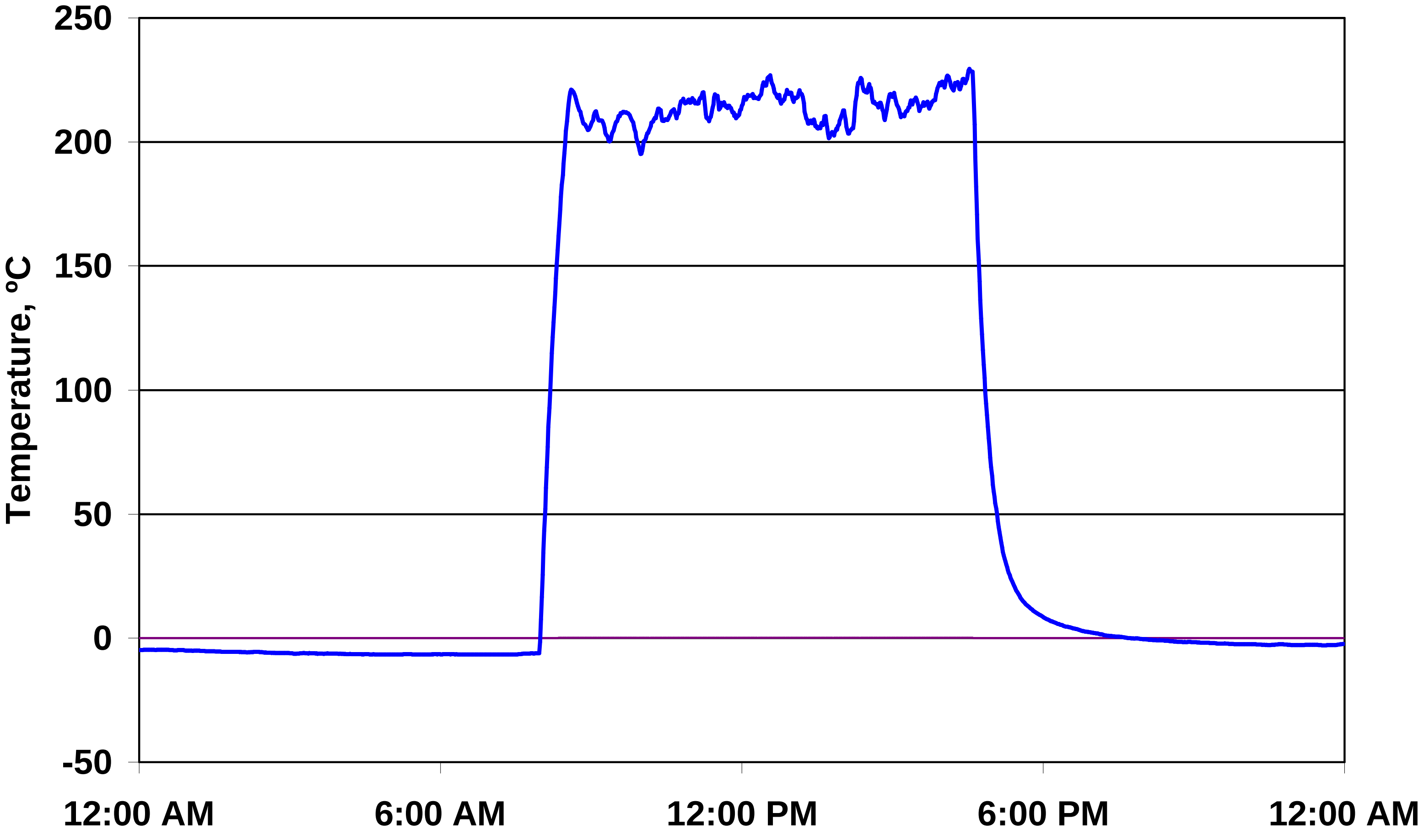


T1. PCAT – Constant Temperature Test

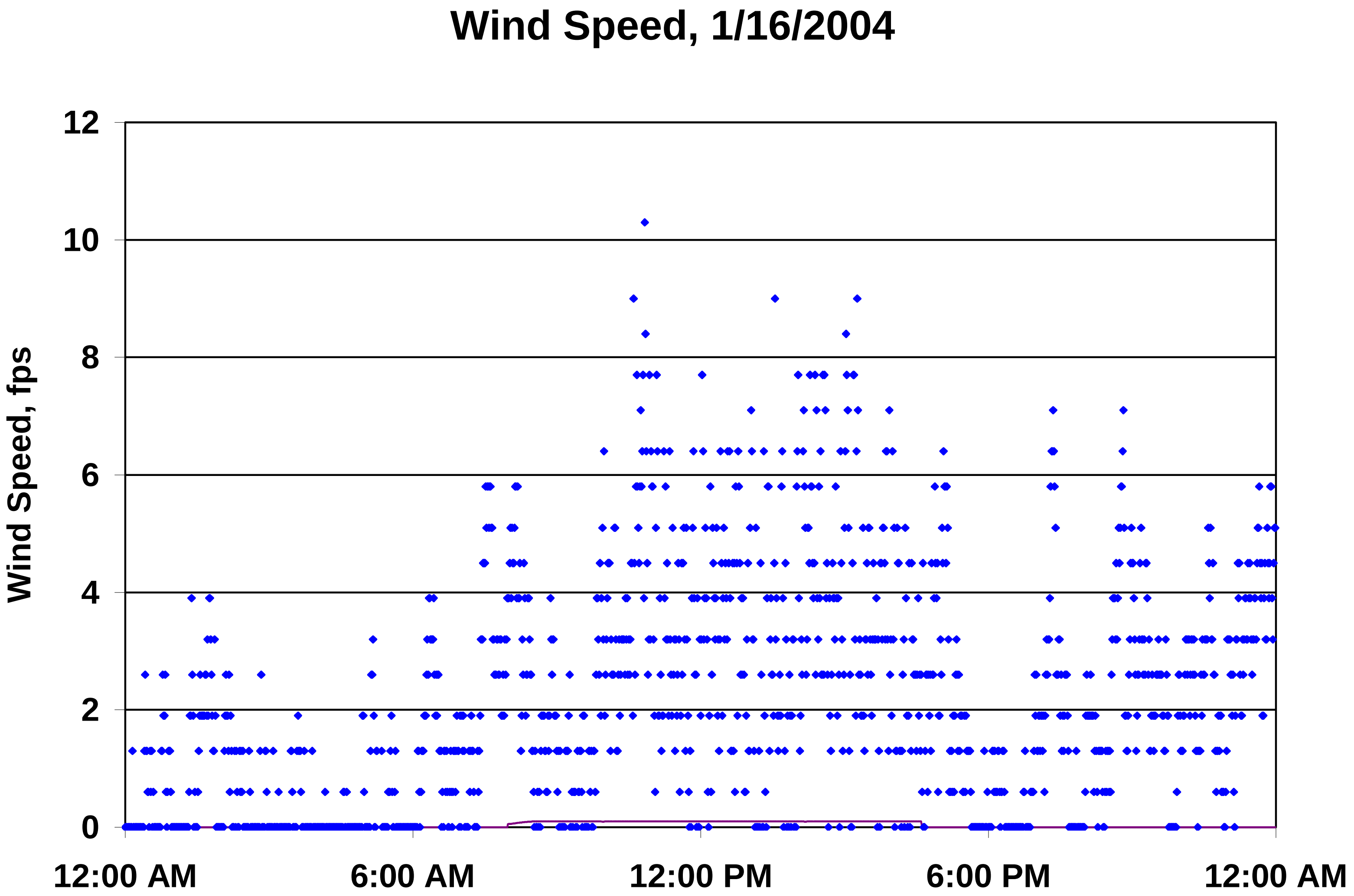


T1. PCAT – Constant Temperature Test

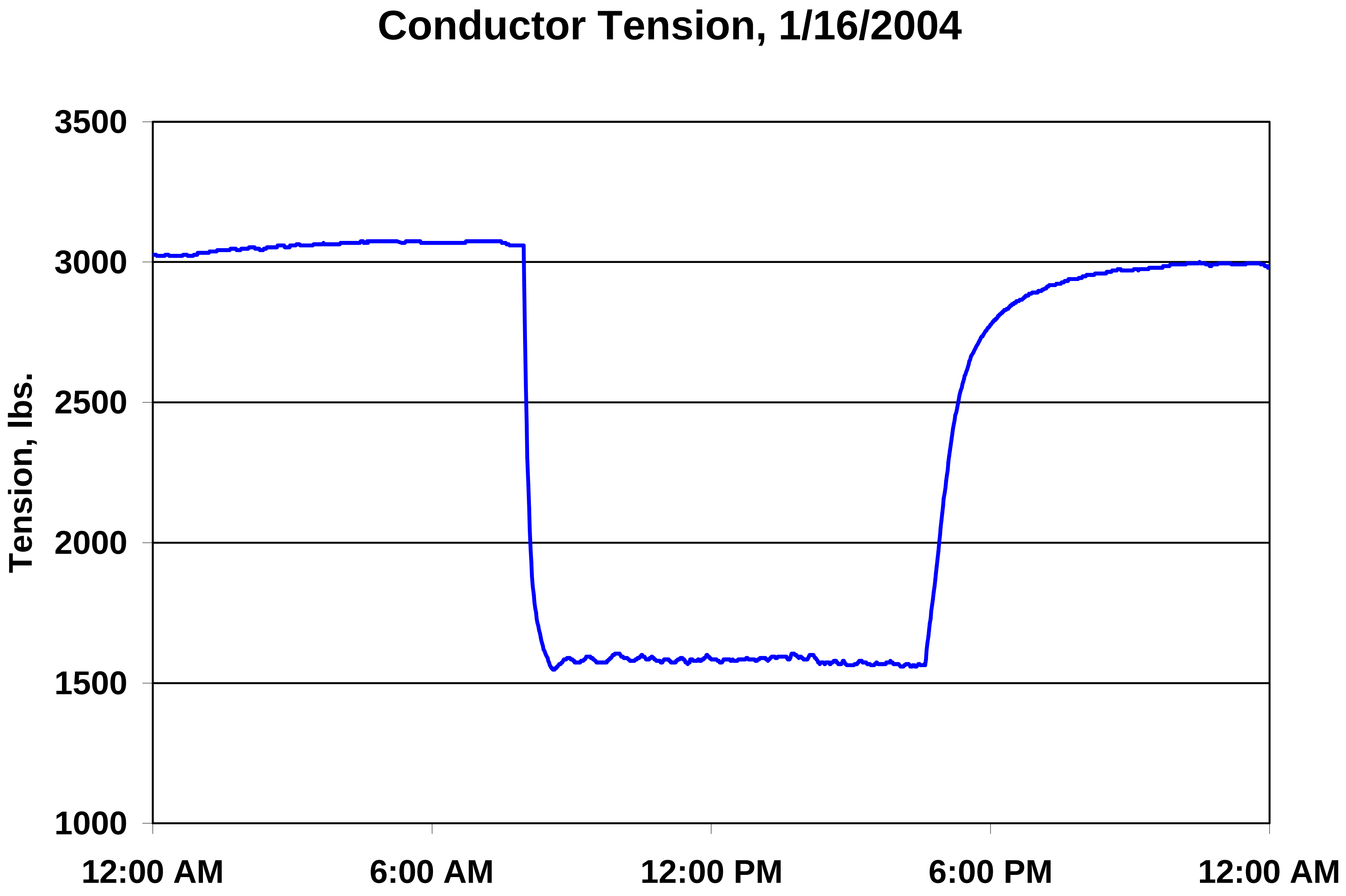
Conductor Core Temperature, 1/16/2004



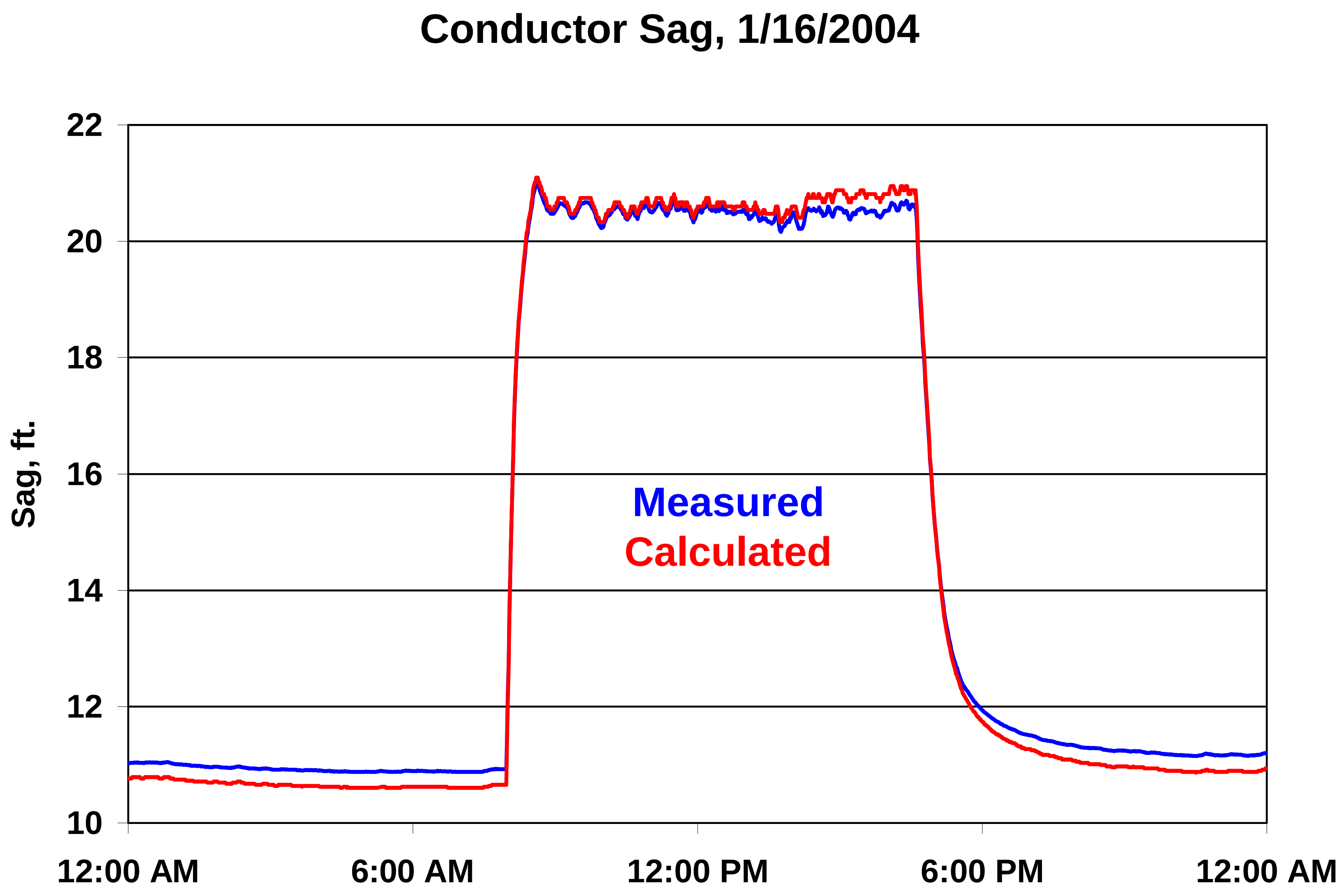
T1. PCAT – Constant <u>Temperature</u> Test



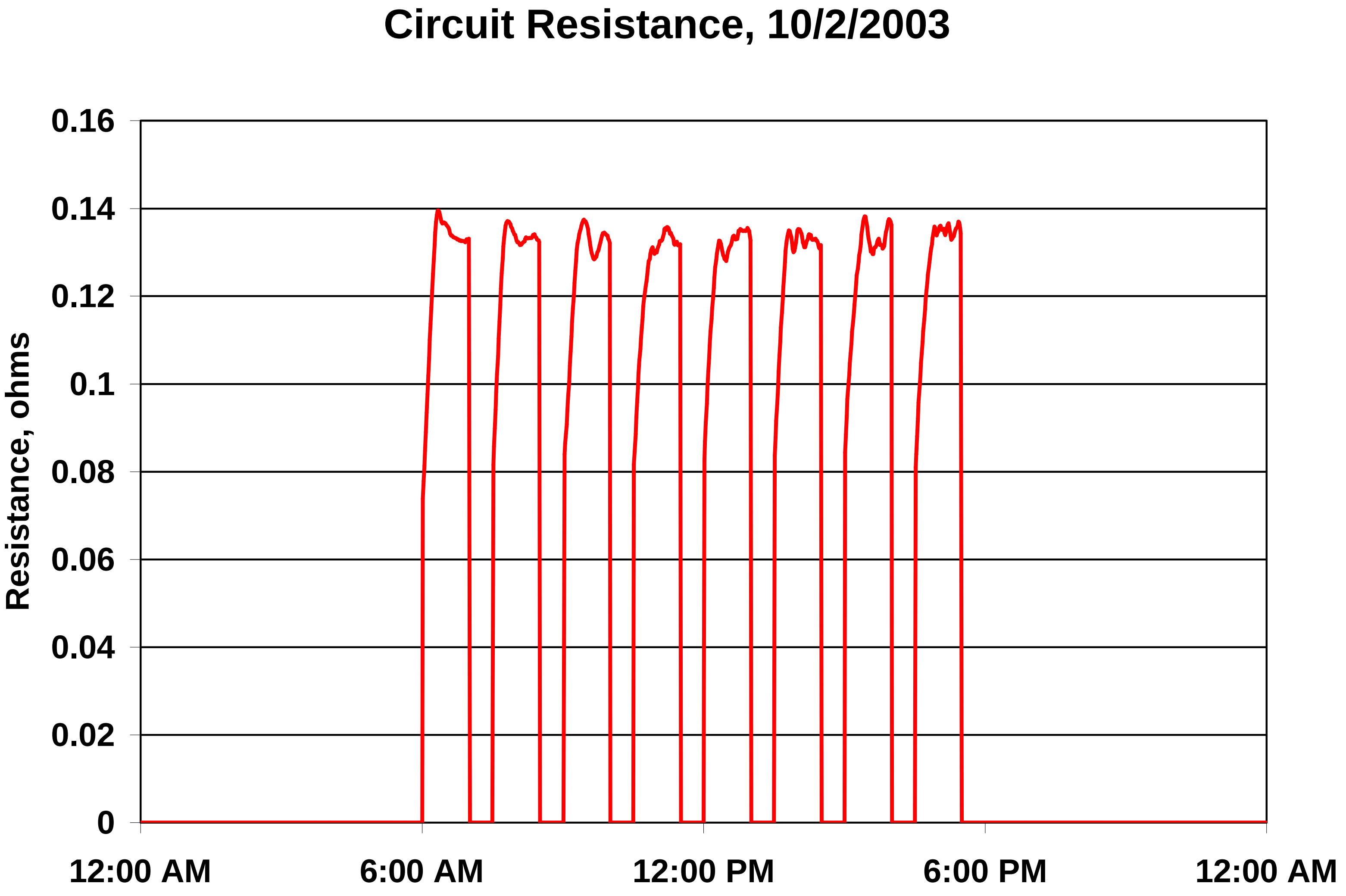
T1. PCAT – Constant Temperature Test



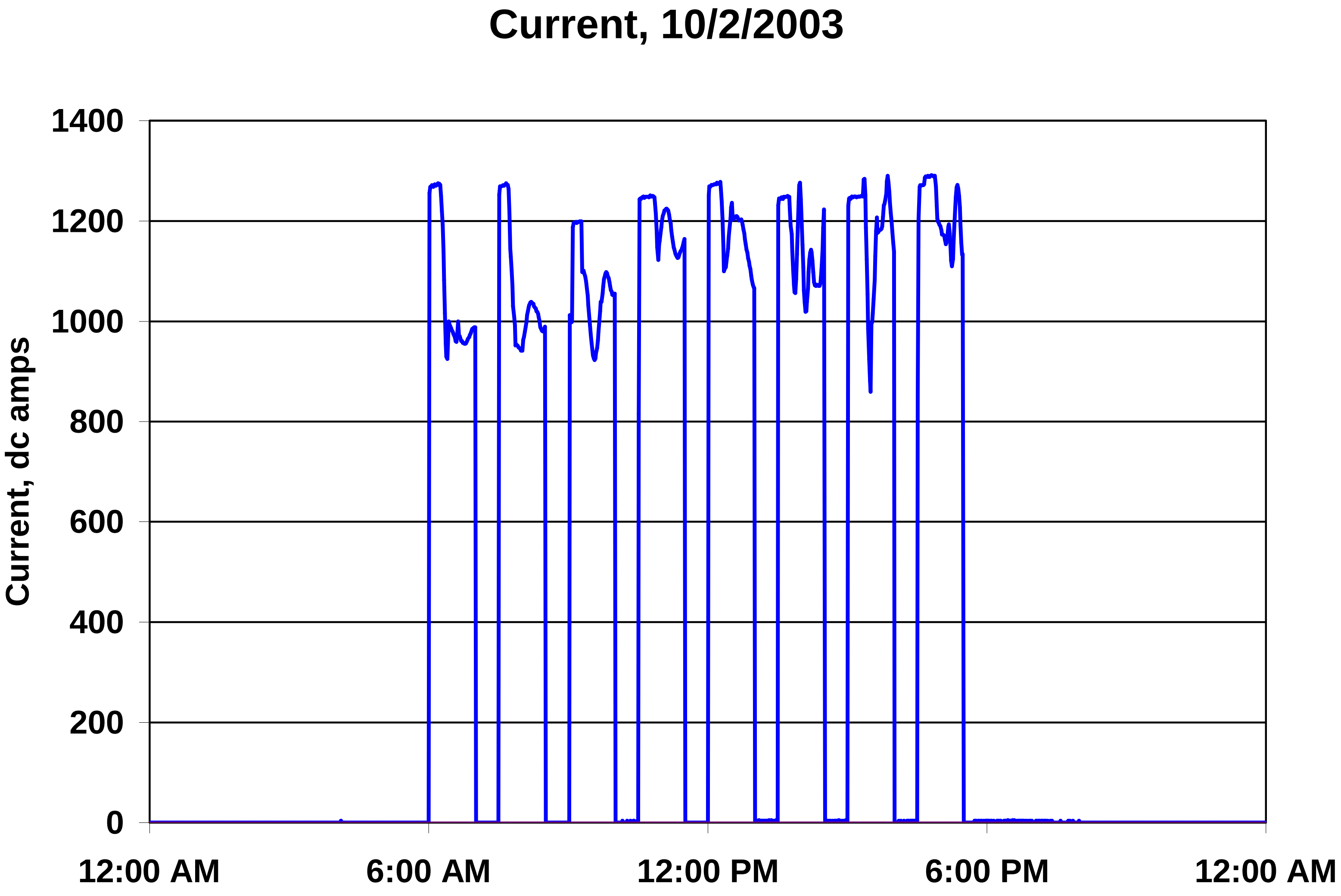
T1. PCAT – Constant Temperature Test



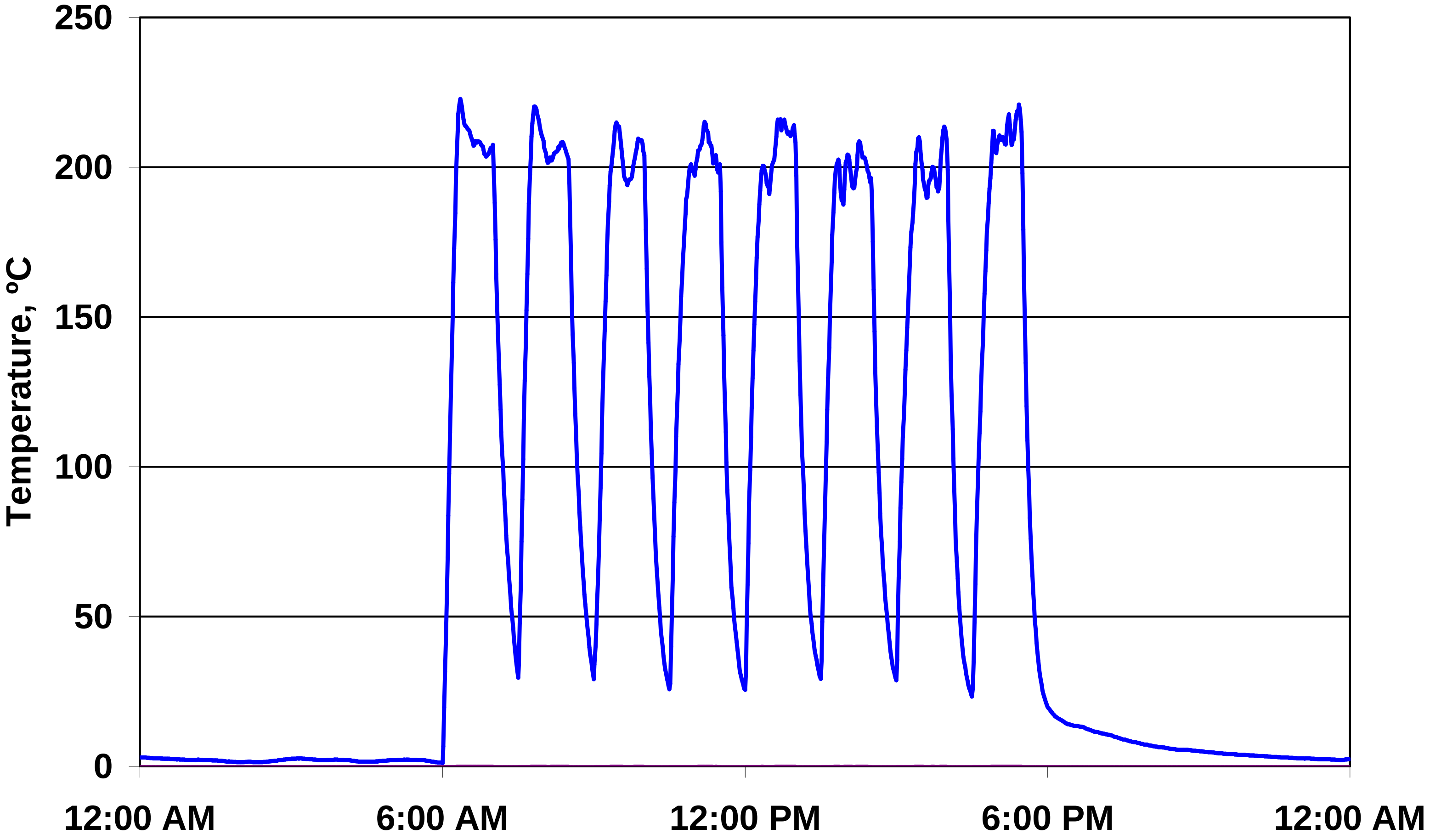
T1. PCAT – Thermal/Mechanical Cycling



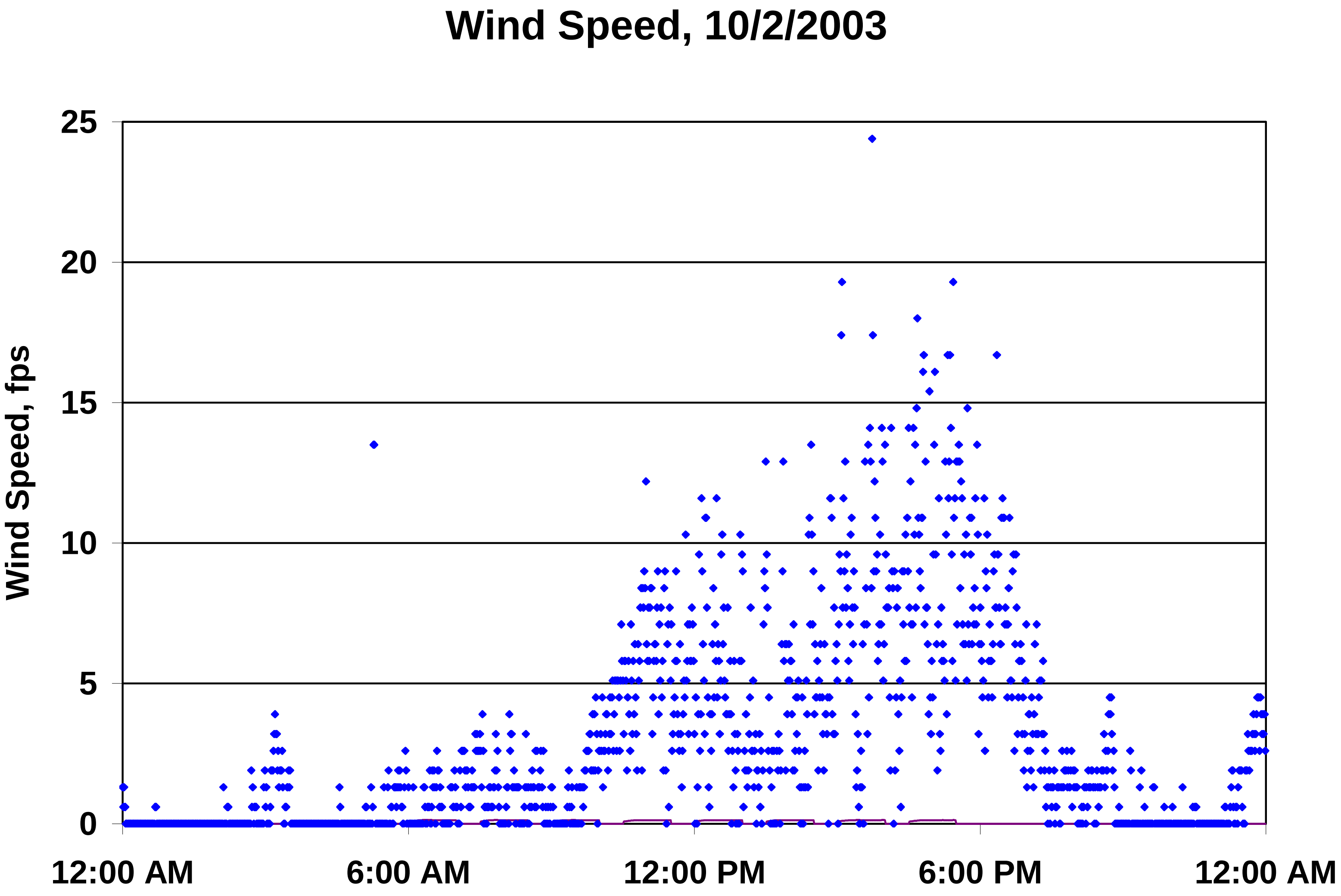
T1. PCAT – Thermal/Mechanical Cycling



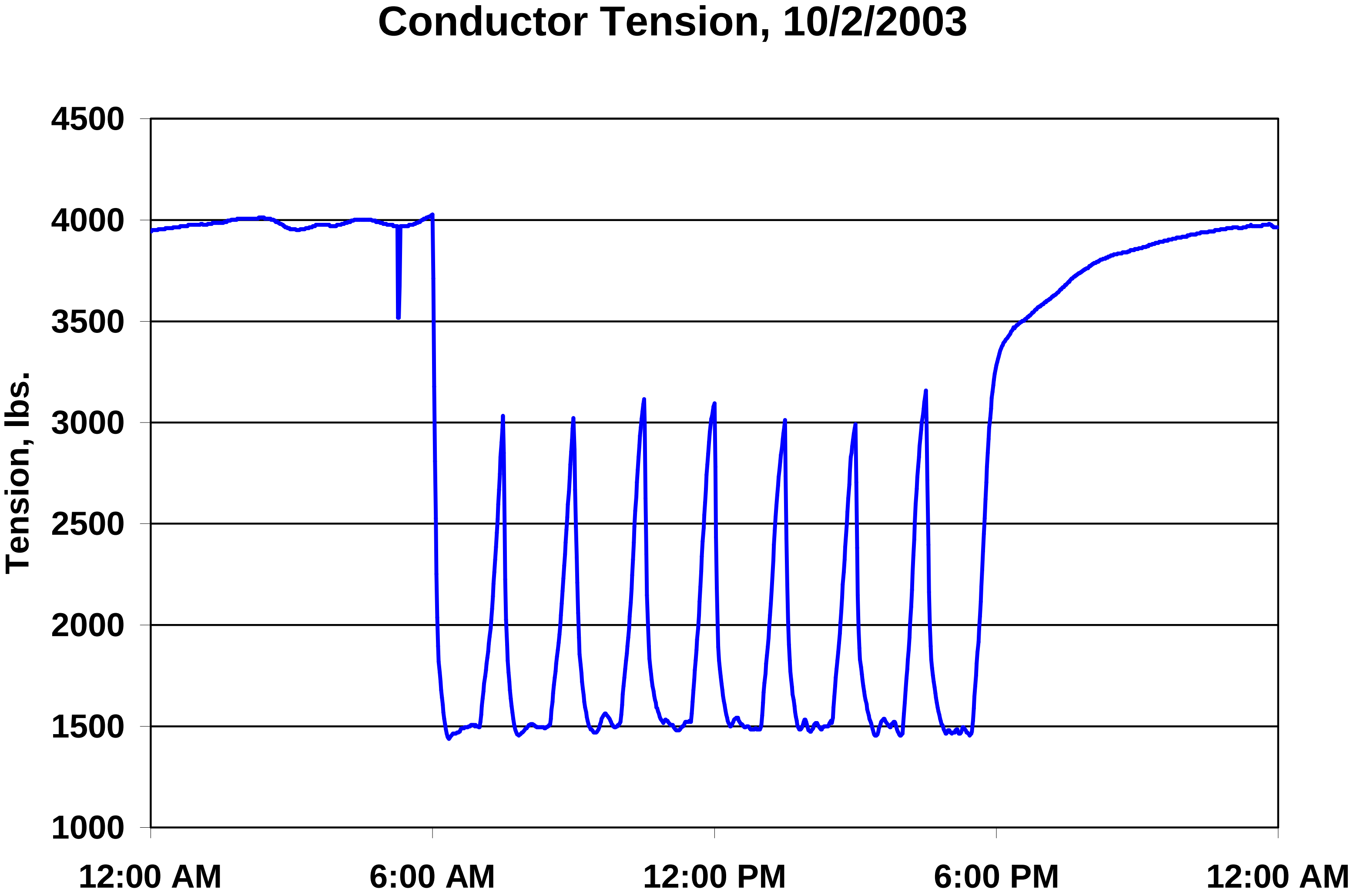
T1. PCAT – Thermal/Mechanical Cycling



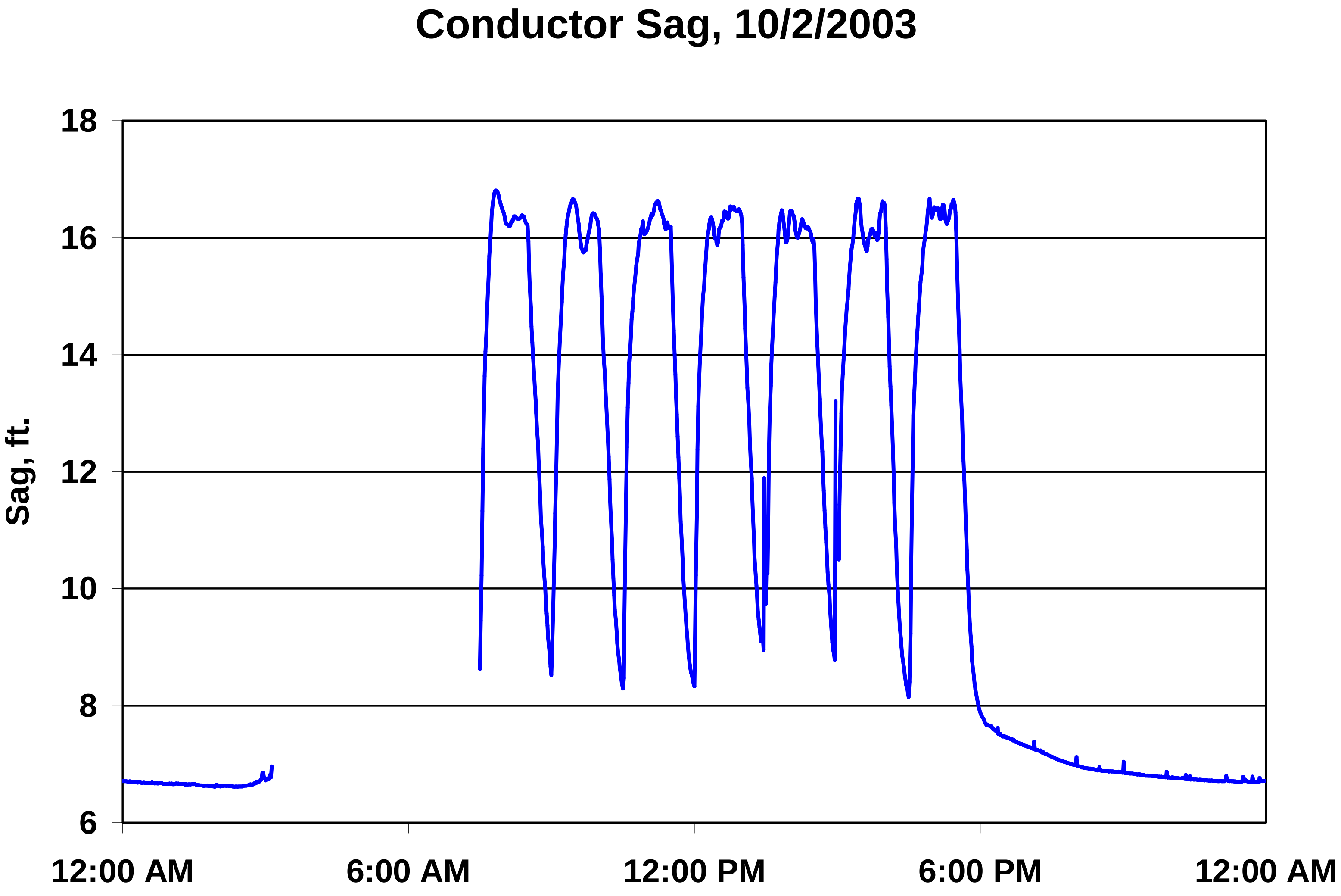
T1. PCAT – Thermal/Mechanical Cycling



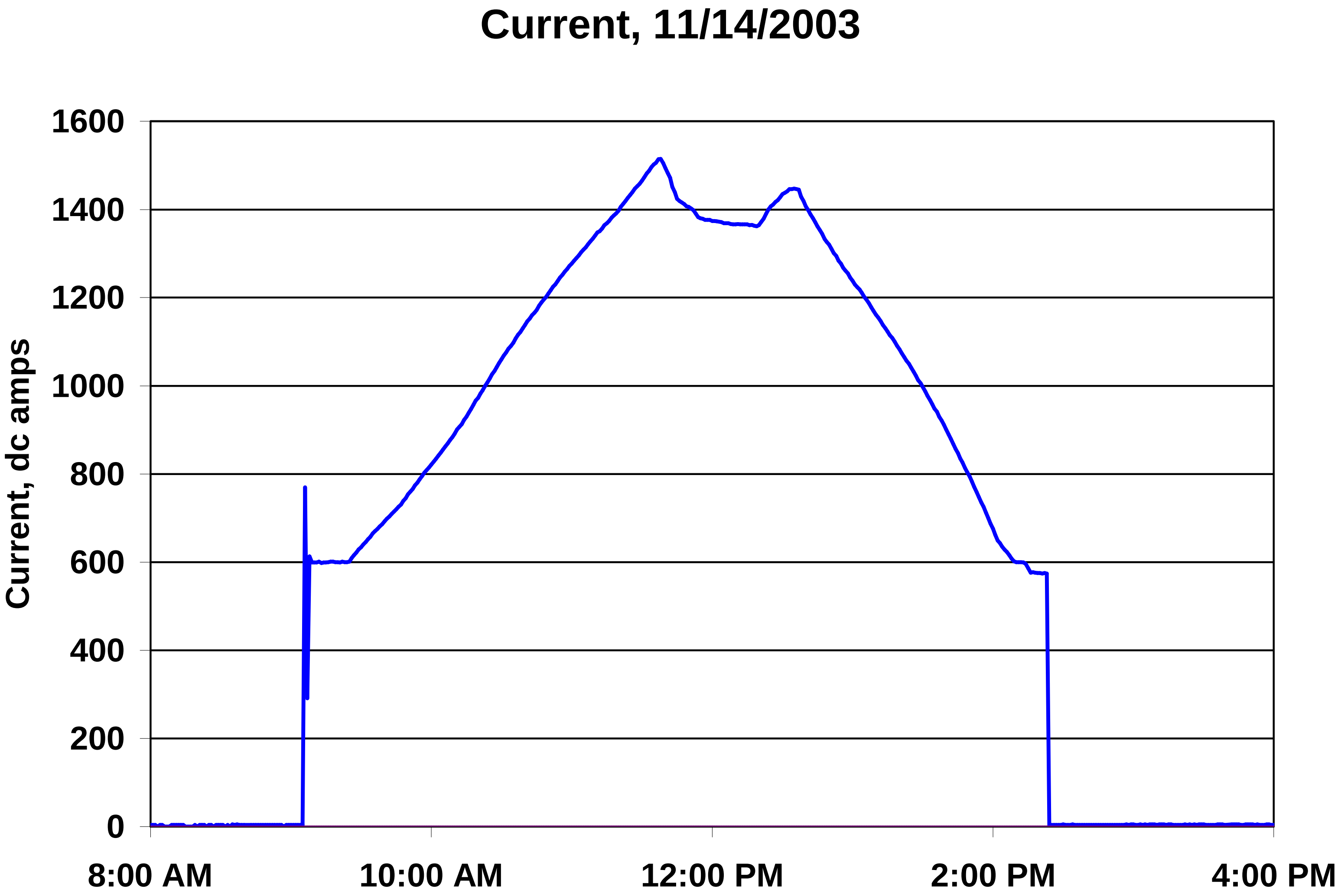
T1. PCAT – Thermal/Mechanical Cycling



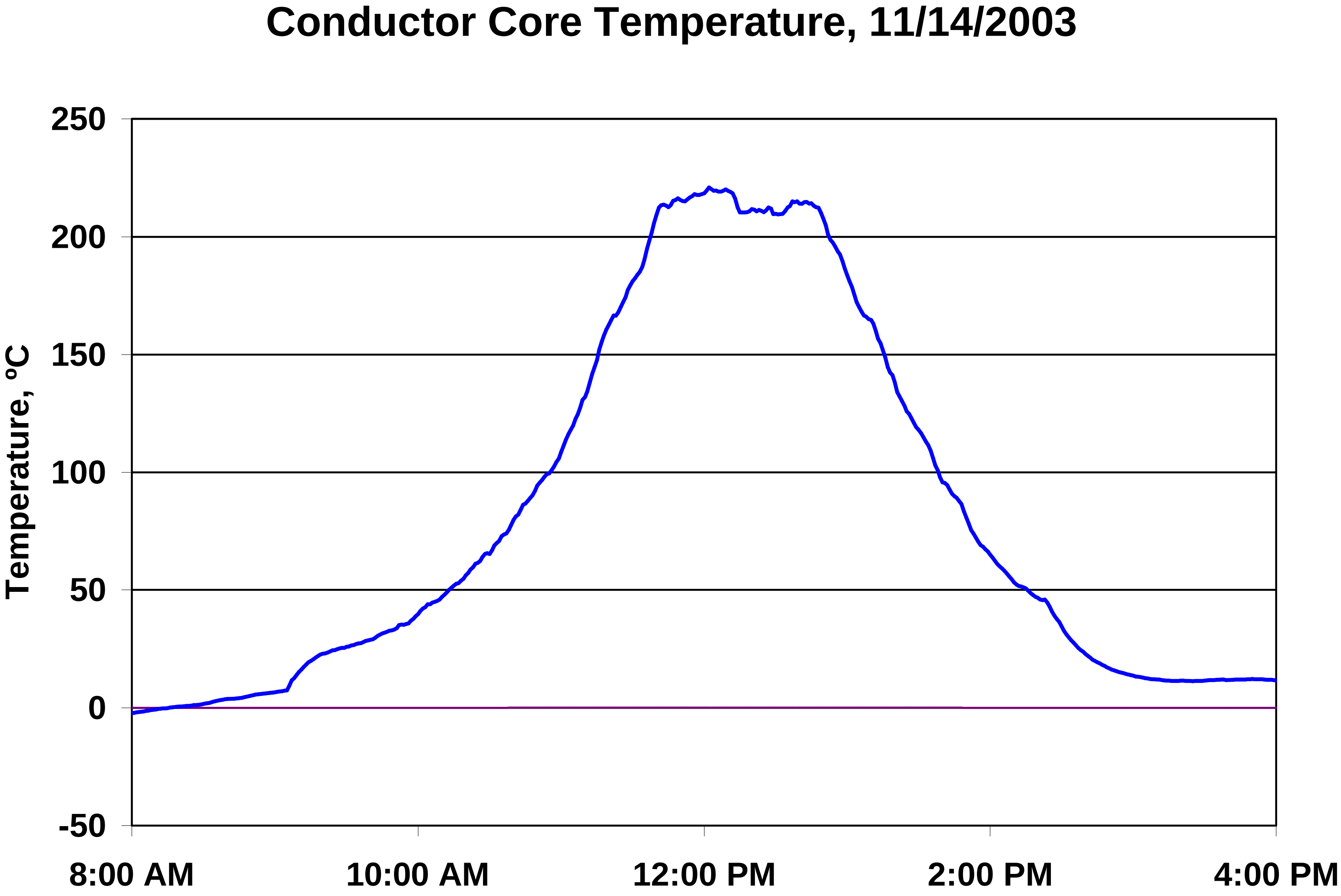
T1. PCAT – Thermal/Mechanical Cycling



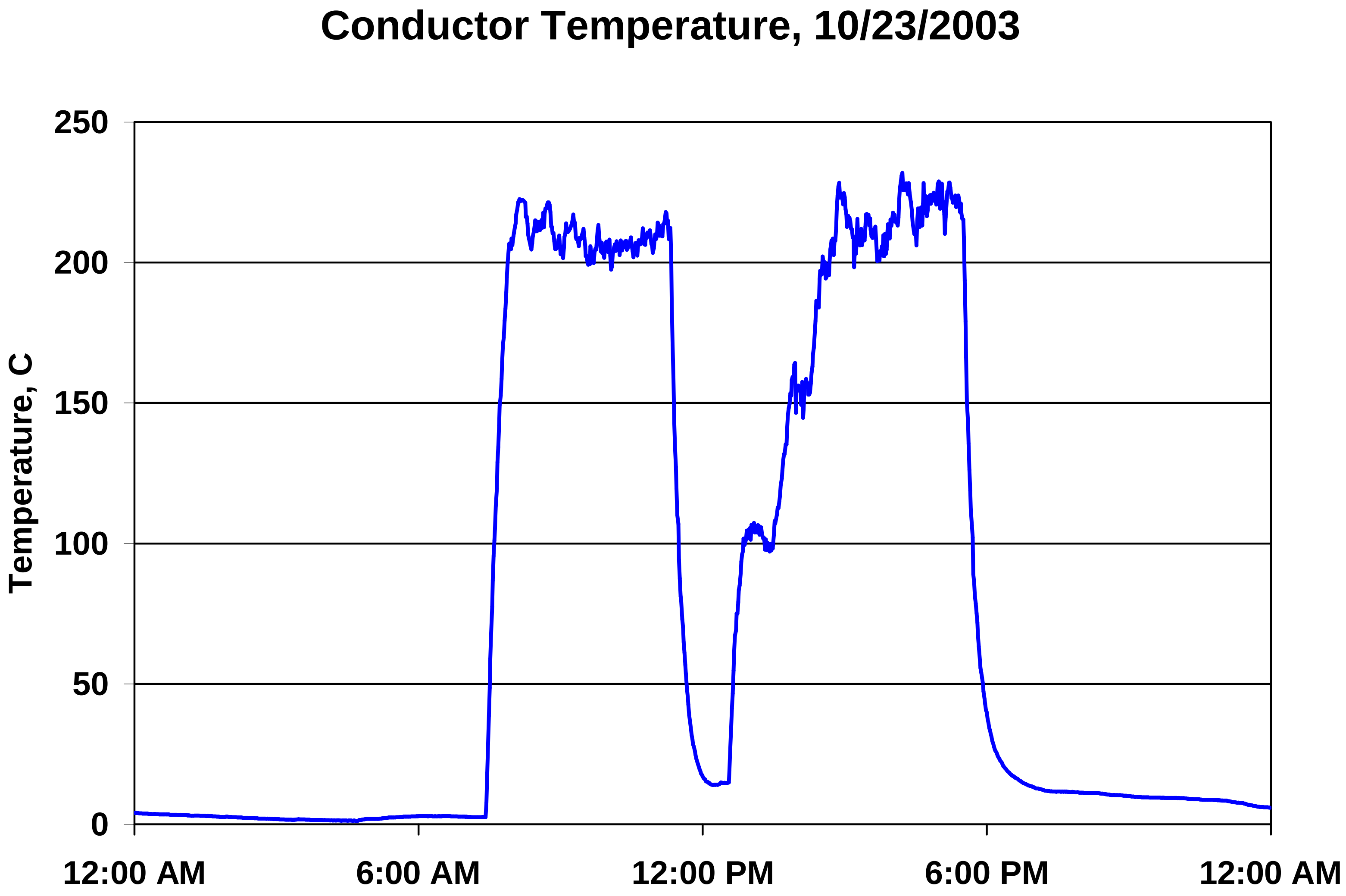
T1. PCAT – Current / Temperature Ramp



T1. PCAT – Current / Temperature Ramp



T1. PCAT – Ramp and Hold



Click To Start Movie of Conductor Sag

T1. PCAT – Summary of Testing Capabilities Used to Date

- **Constant Current**
- **Constant Temperature**
- **Thermal / Mechanical Cycling**
- **Current / Temperature Ramp**
- **Current / Temperature Ramp and Hold**

Laser at mid-span measure conductor sag

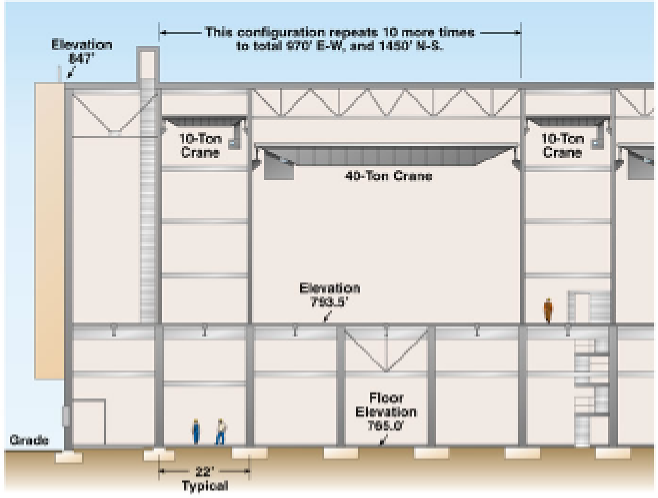
T2. - Indoor PCAT

National Transmission Technology Research Center

Indoor PCAT – indoor Powerline Conductor Accelerated Test Facility

T2. Indoor PCAT
Facility Offers Unique Capabilities

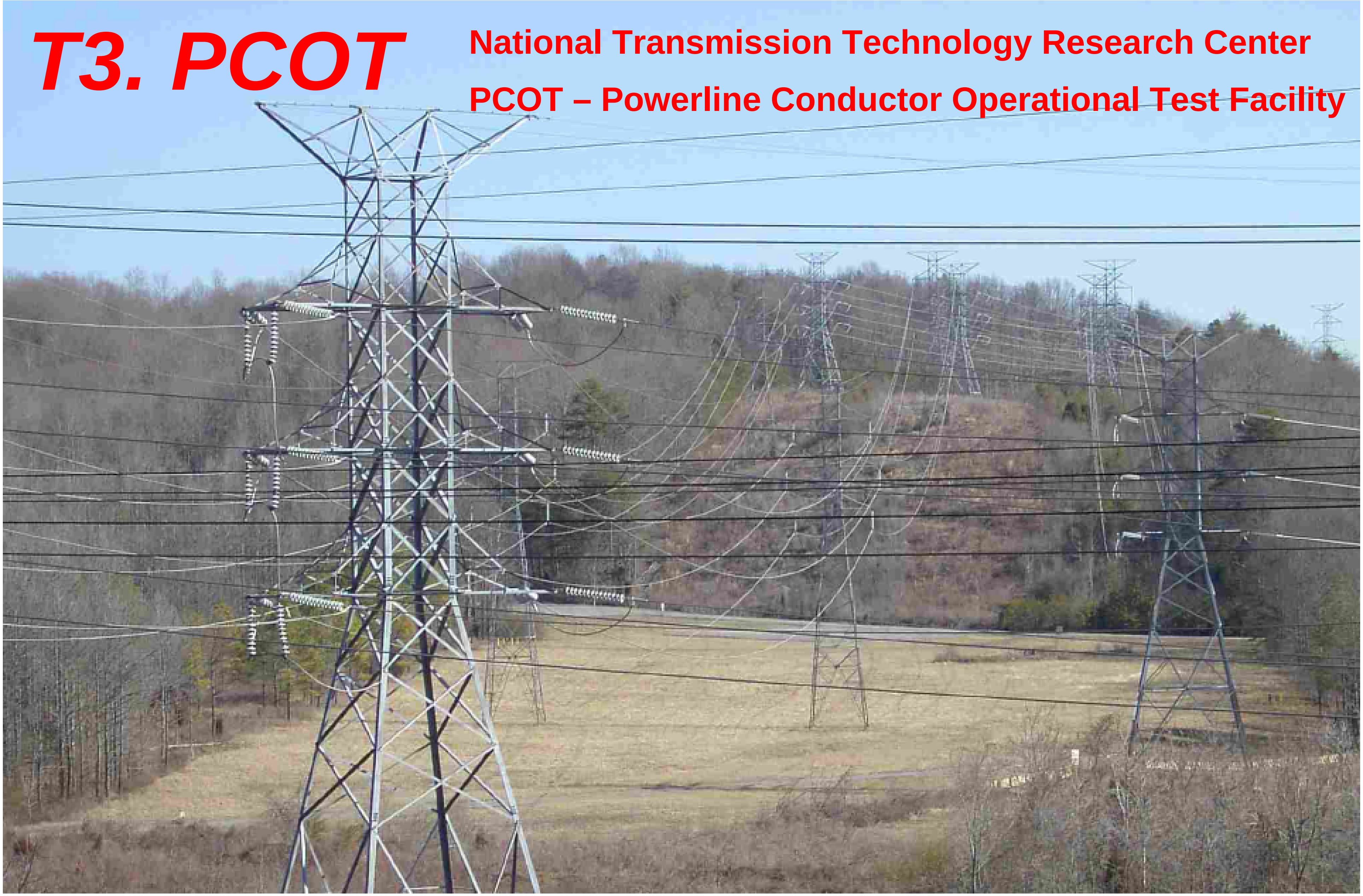
- Indoor version of outdoor Powerline Conductor Accelerated Test facility
- 54 ft. high, 40 ft. wide and 1456 ft. long bay
- No wind, rain, lightning, solar, temperature gradients
- Tighter measurement tolerances
- Easier instrumentation
- Controlled accelerated aging of components



T3. PCOT

National Transmission Technology Research Center

PCOT – Powerline Conductor Operational Test Facility



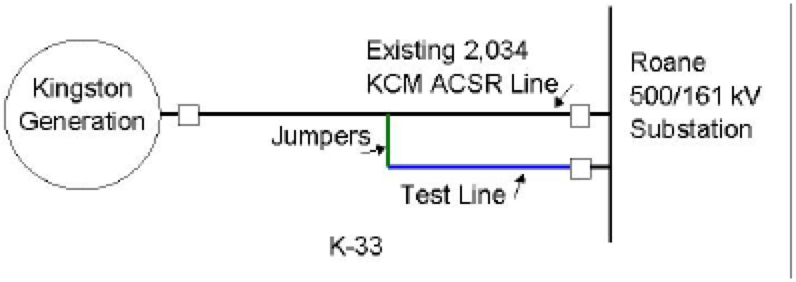
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

TVA

UT-BATTELLE

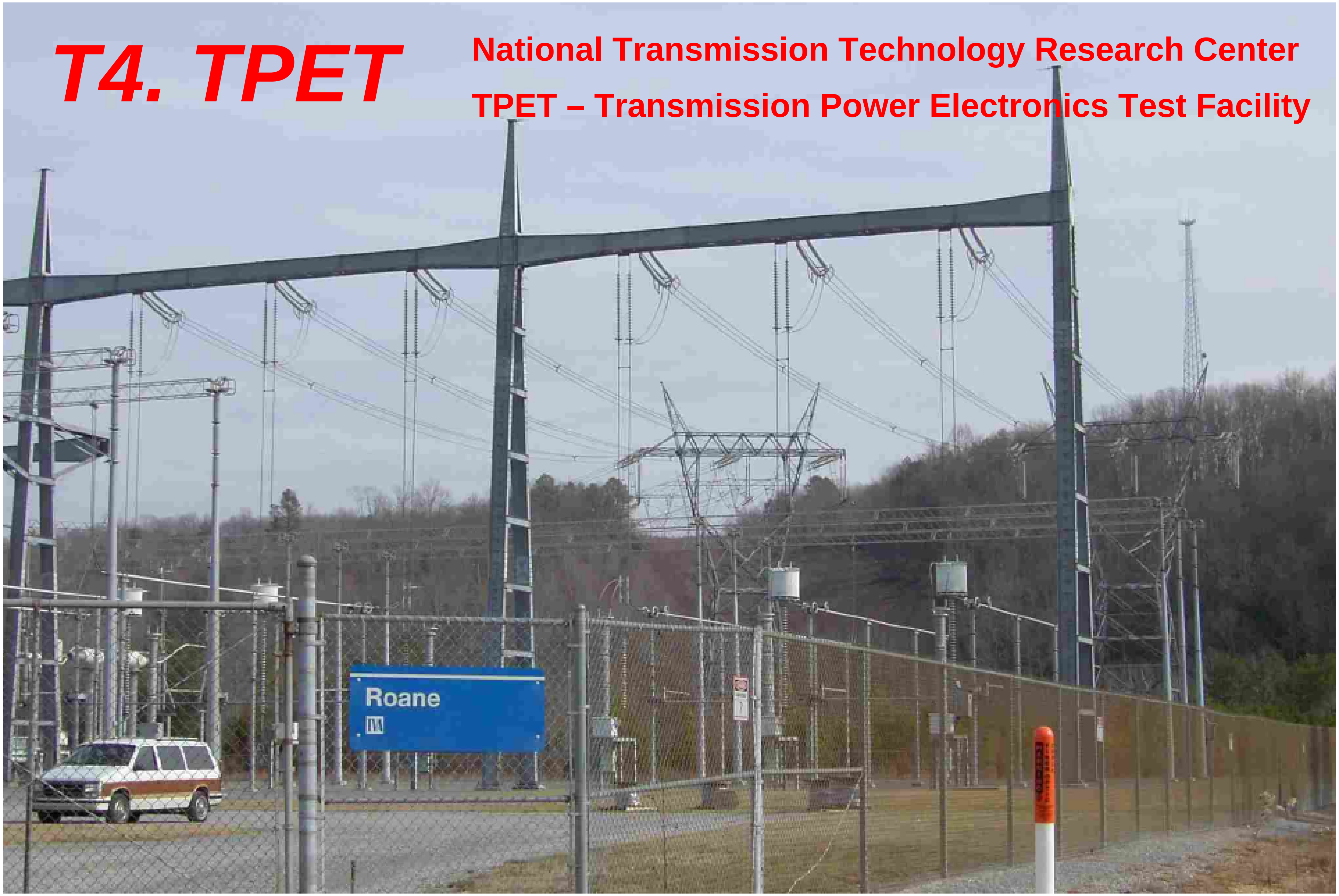
T3. PCOT Facility

- **Powerline Conductor Operations Testing**
  - Test conductor at operating voltage and load current
  - TVA 161-kV lines between TVA Kingston power plant and TVA Roane substation
  - On DOE property - no public exposure
  - Unique location - ability to switch test in and out of service and control loading
  - Exceptional size - 2034 KCM ACSR - will not limit advanced conductor test
  - Plan to heavily instrument facility - long life and multiple uses



CAT-1 Transmission Line Monitoring System has been purchased.

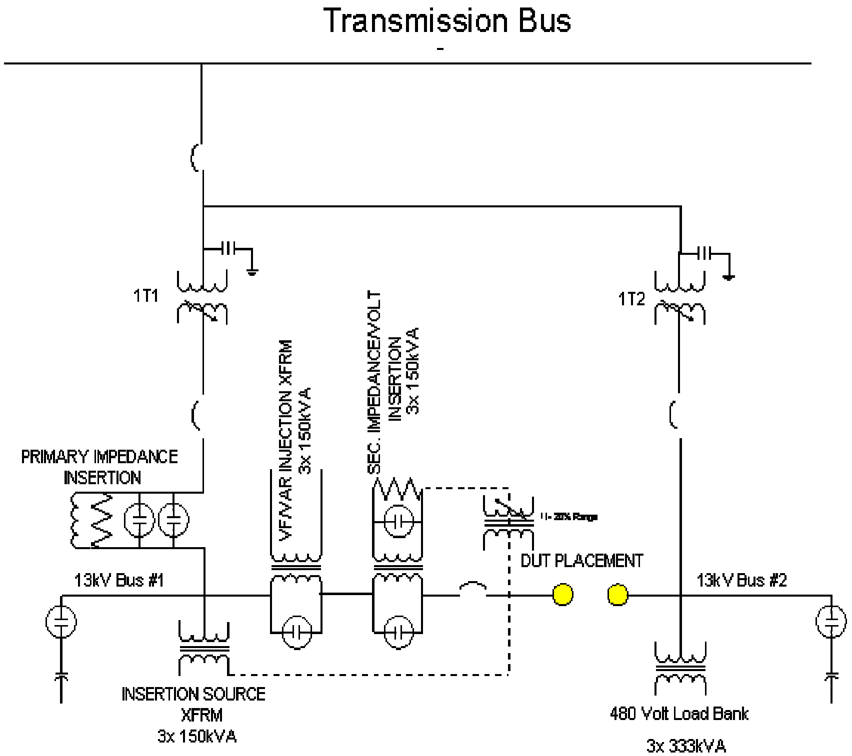
T4. TPET



National Transmission Technology Research Center

TPET – Transmission Power Electronics Test Facility

T4. Transmission Power Electronics Test Facility



- **13 kV for transmission level devices**
- **2 power transformers allow flow control**
- **Dynamic testing capabilities**
- **Power quality of neighboring loads *not* degraded**

National Transmission Technology Research Center

T1.
Outdoor PCAT

Powerline Conductor Accelerated Test Facility

T2.
Indoor PCAT

Powerline Conductor Accelerated Test Facility

T3.
PCOT
(TVA lines)

Powerline Conductor Operational Test Facility

T4.
TPET
(Substation)

Transmission Power Electronics Test Facility

Questions

Contact Information

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  - kisnerra@ornl.gov

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  - rizydt@ornl.gov

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  - (865) 574-9338 Fax
  - stovalljp@ornl.gov

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ESTD
Engineering Science & Technology Division

Appendix C.3

DOE Peer Review Presentation – October 12, 2005

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Transmission Test Facility

U.S. Department of Energy
Transmission Reliability Program
Peer Review

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Oak Ridge National Laboratory

ORNL Project Team
D. Tom Rizy
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1221 22nd St. NW
Washington, D.C. 20005

October 12, 2005

National Transmission Grid Study

One of the 51 Recommendations

“DOE will develop national transmission-technology testing facilities that encourage partnering with industry to demonstrate advanced technologies in controlled environments.

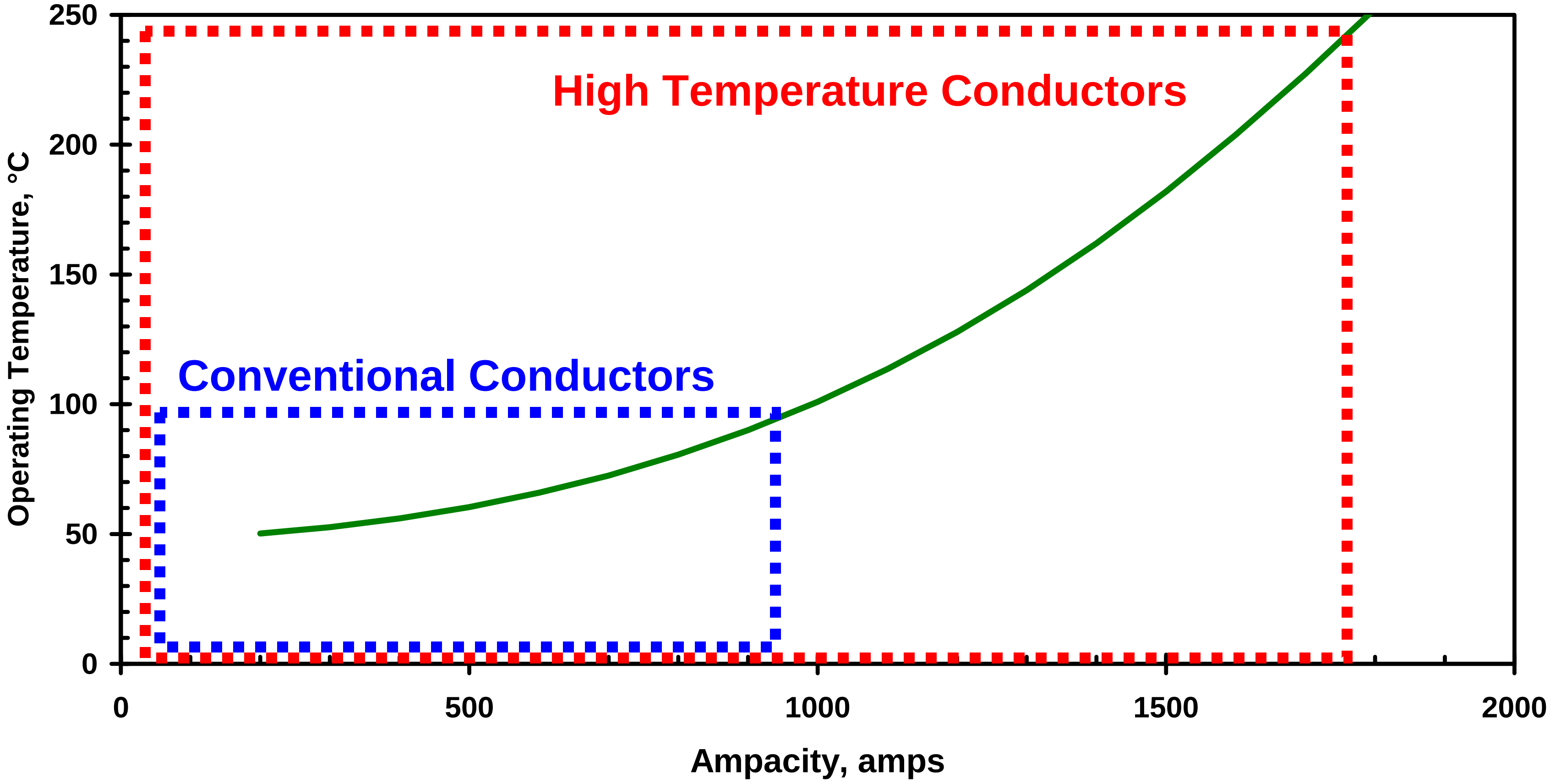
Working with TVA, DOE will create an industry cost-shared transmission line testing center at DOE ’s Oak Ridge National Laboratory (with at least a 50 percent industry cost share).*”

*National Transmission Grid Study, U.S. DOE, May 2002 www.ntgs.doe.gov

New conductors are available and being developed to improve on today's conductors

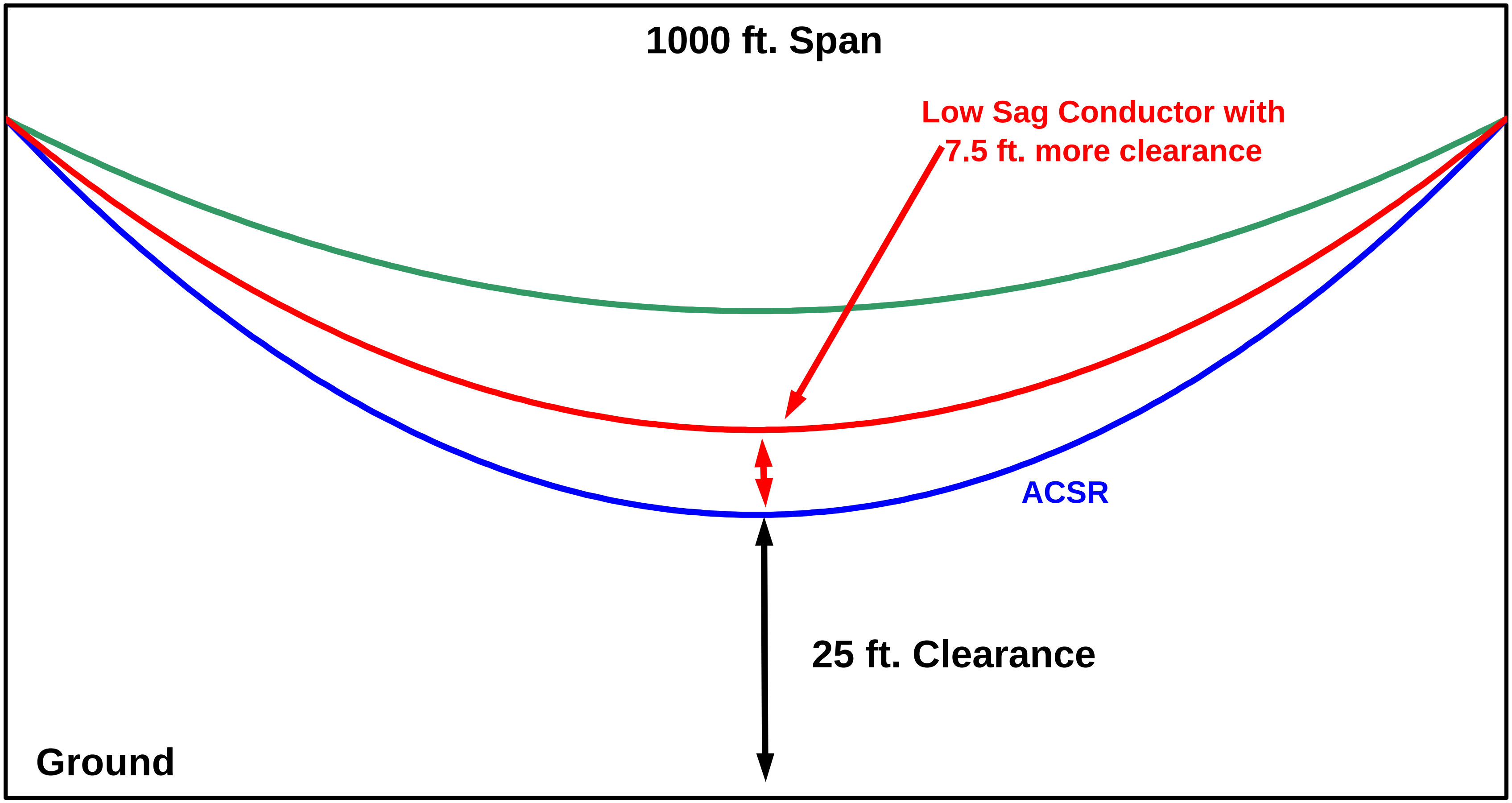
- **#1 – Conductor Operating Temperature Limits Allowable Current**
  - **Raise operating temperature of aluminum by**
    - **Fully anneal the aluminum – lower strength**
    - **Add small amount of zirconium to aluminum – retains strength**
- **#2 – Conductor Sag Limits Allowable Current**
  - **The solution is to replace steel with a different material having a lower coefficient of thermal expansion (CTE)**
- **#3 Trapezoidal Shaped Wires**
  - **Pack more aluminum into same conductor diameter**
  - **More aluminum means more current**
- **#4 Gap Conductor**
  - **Reduce sag by using only the steel to hold conductor**
  - **Build a gap between steel core and aluminum**

#1 Benefit of Higher Operating Temperatures is Higher Current Rating

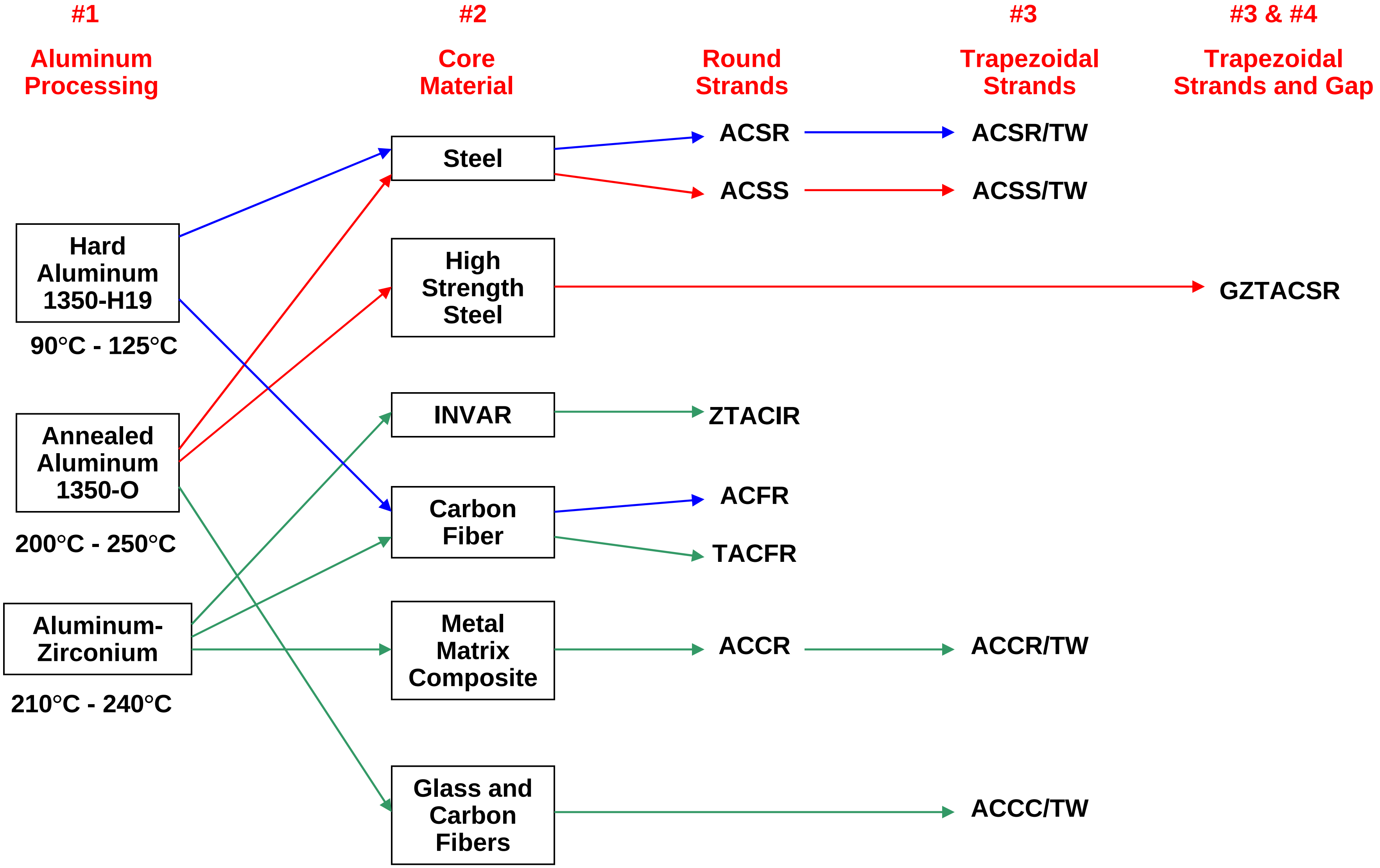


Need to test / verify new conductors over entire operating range

#2 Benefit of a Conductor that Expands at One-Half the Rate of ACSR



Conductor Road Map



#1
Aluminum Processing

#2
Core Material

Round Strands

#3
Trapezoidal Strands

#3 & #4
Trapezoidal Strands and Gap

Hard Aluminum 1350-H19
90°C - 125°C

Annealed Aluminum 1350-O
200°C - 250°C

Aluminum-Zirconium
210°C - 240°C

Steel

High Strength Steel

INVAR

Carbon Fiber

Metal Matrix Composite

Glass and Carbon Fibers

ACSR → ACSR/TW

ACSS → ACSS/TW

GZTACSR

ZTACIR

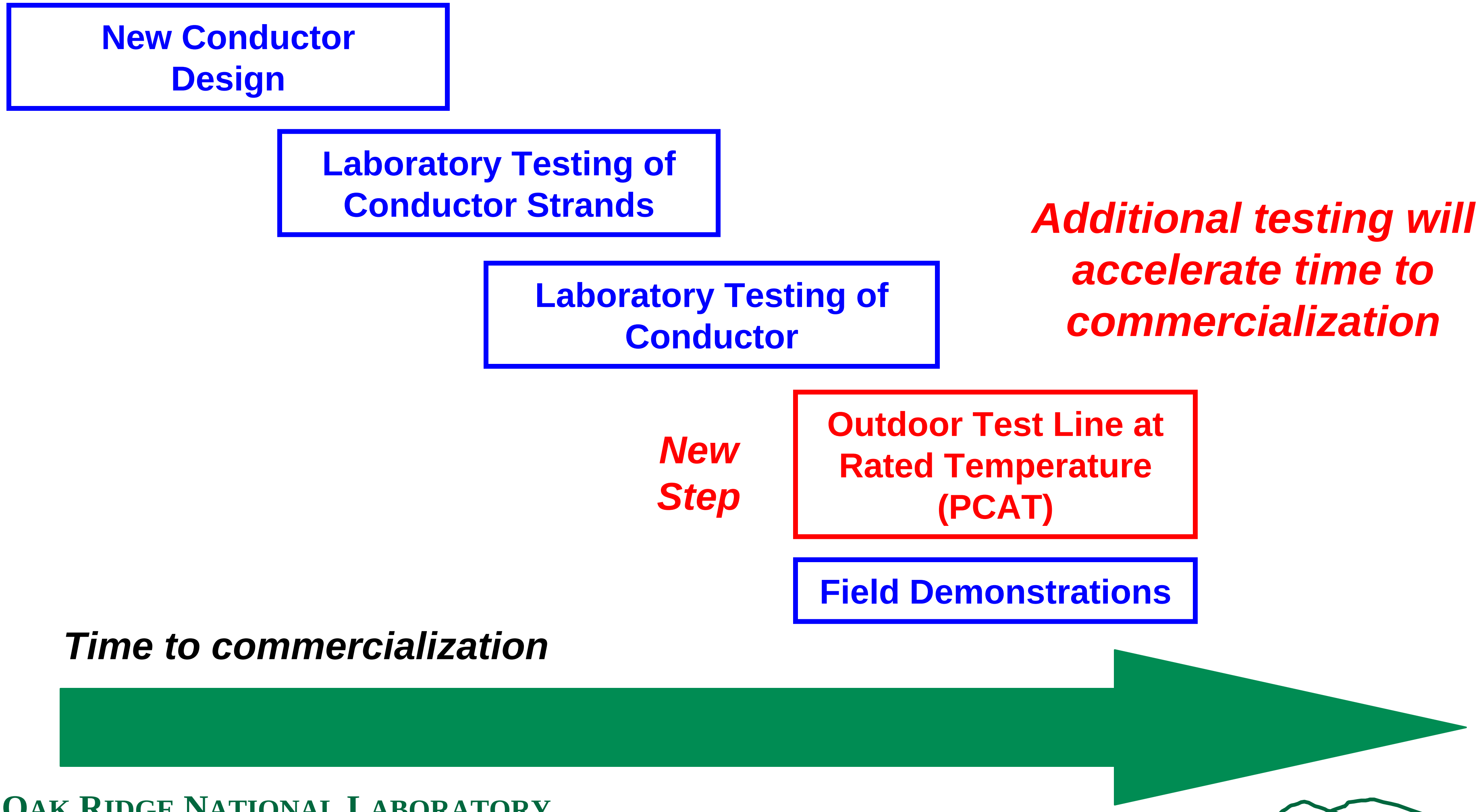
ACFR

TACFR

ACCR → ACCR/TW

ACCC/TW

Bringing a New Conductor to Market



New Conductor Design

Laboratory Testing of Conductor Strands

Laboratory Testing of Conductor

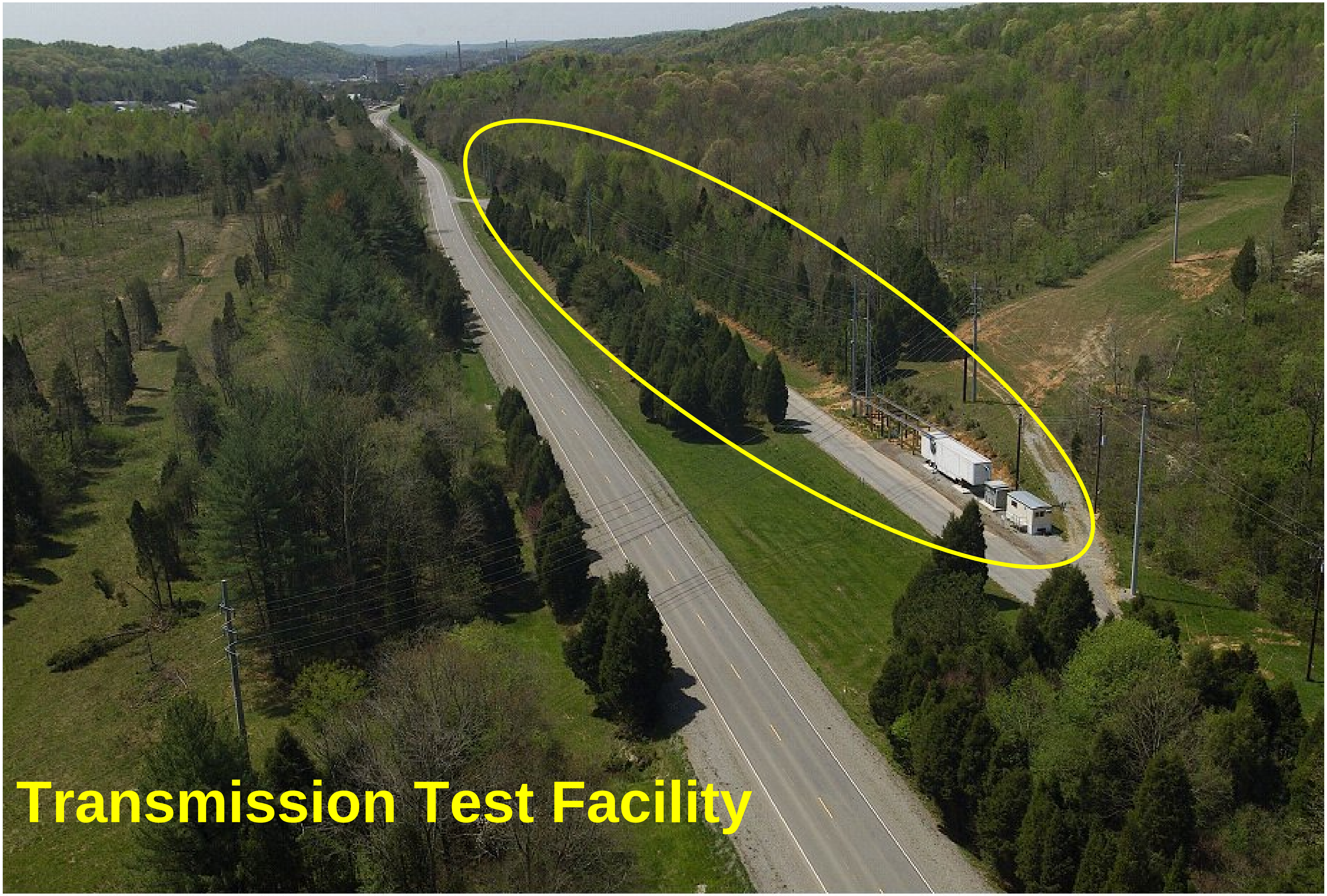
New Step

Outdoor Test Line at Rated Temperature (PCAT)

Field Demonstrations

Additional testing will accelerate time to commercialization

Time to commercialization

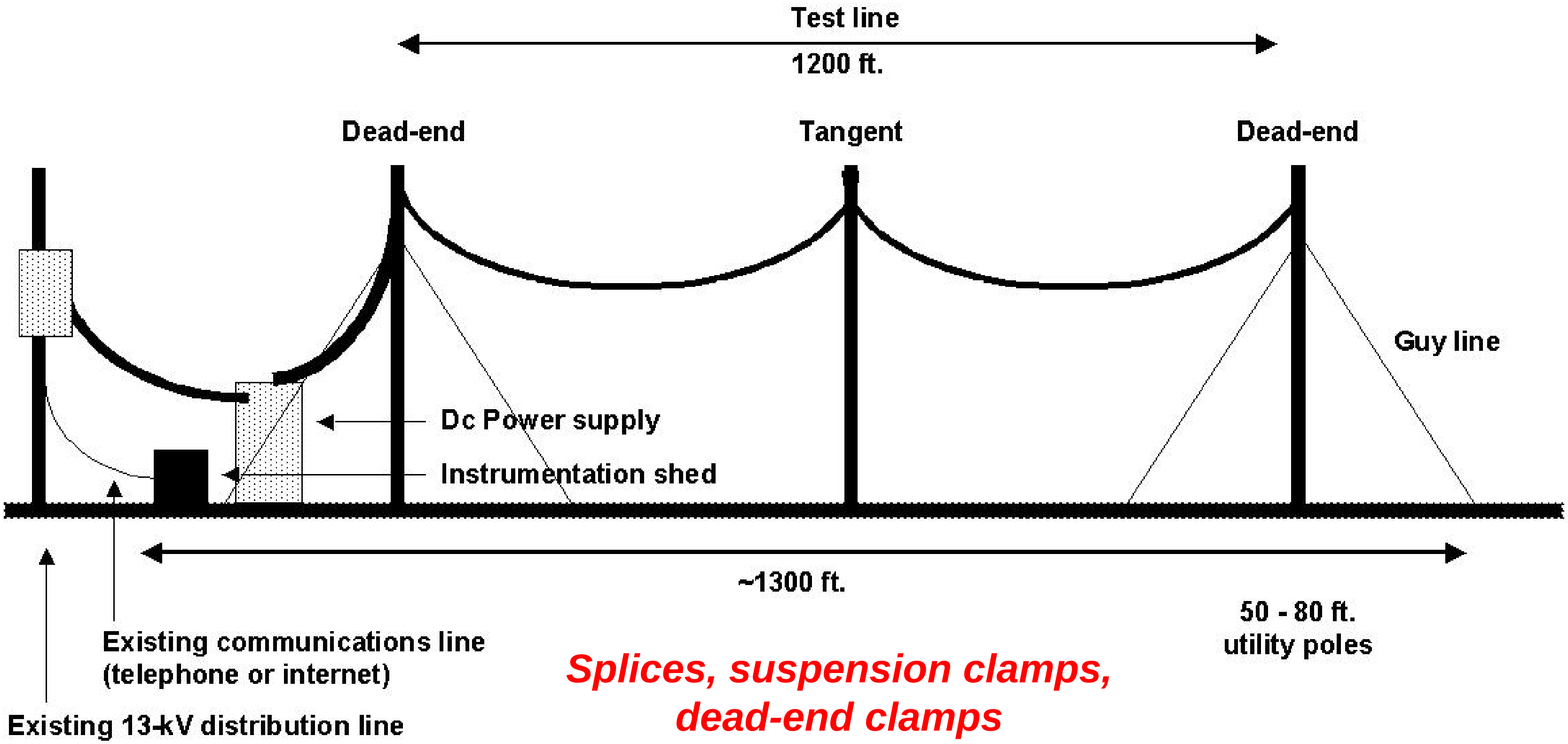


Transmission Test Facility

Profile View of Outdoor Test Line

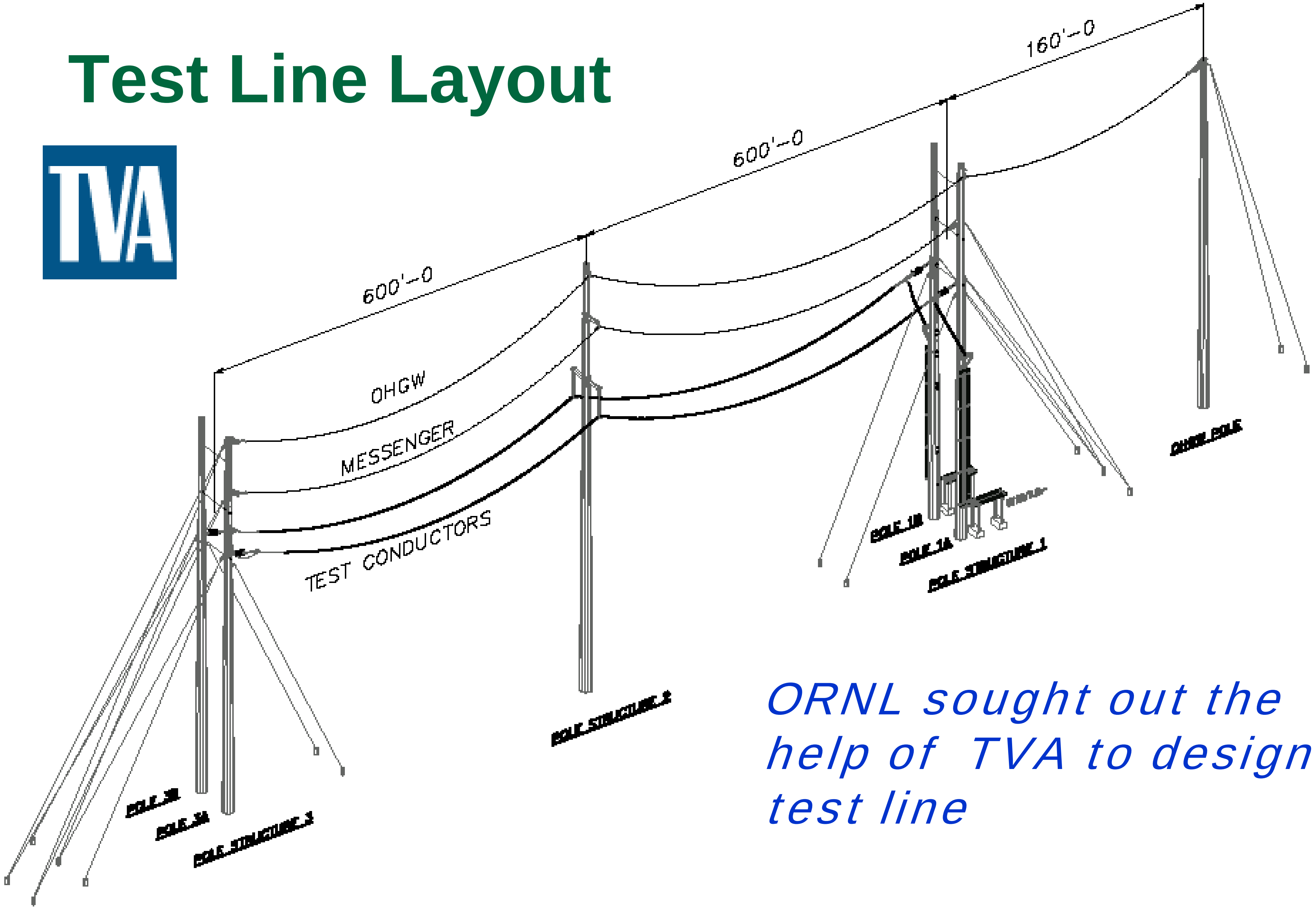
Transmission Test Facility

Initial Concept for Test Facility
Developed with 3M Company



Splices, suspension clamps, dead-end clamps

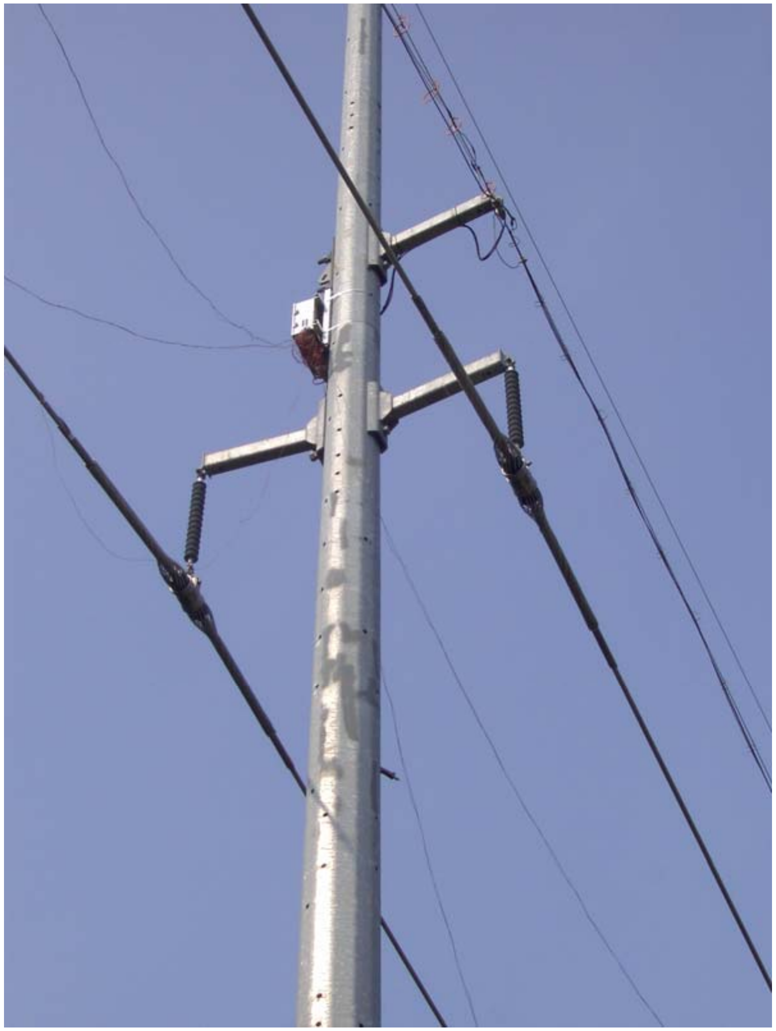
Test Line Layout



ORNL sought out the help of TVA to design test line

Structure #1
Alcoa Dead-Ends and Jumpers

Structure #2
PLP Suspensions



Structure #3
PLP Dead-Ends and Alcoa Terminal Pads

Two Splices Near Mid Spans


PLP Splice


Alcoa Splice

Installation of test conductor and accessories takes a transmission line construction crew three or four days

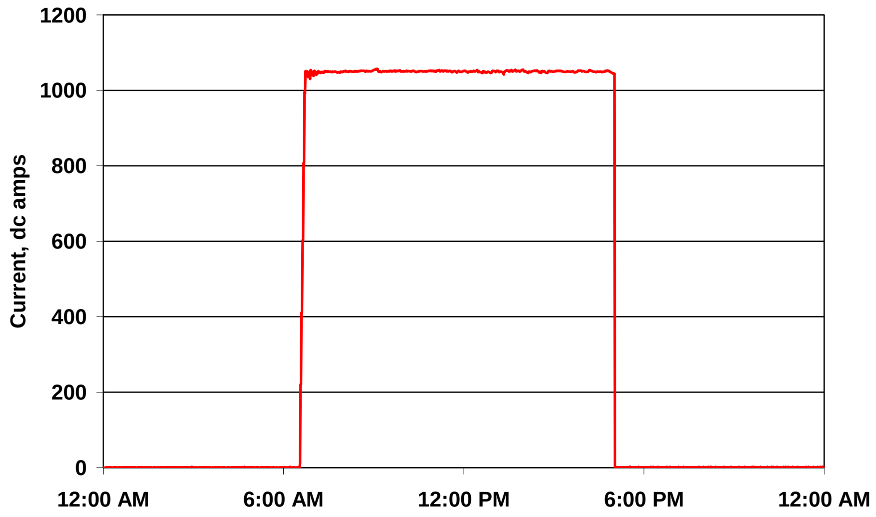
3M 1272 kcmil ACCR Installed on Aug. 9-11, 2004

TVA Line Crew - Jonathan M. Rains, James E. Hampton, Randel Hurd, Alan W. Brown, Kevin R. Hodges, Robert Gunter, Lucus Marlow, and Richard B. Stewart

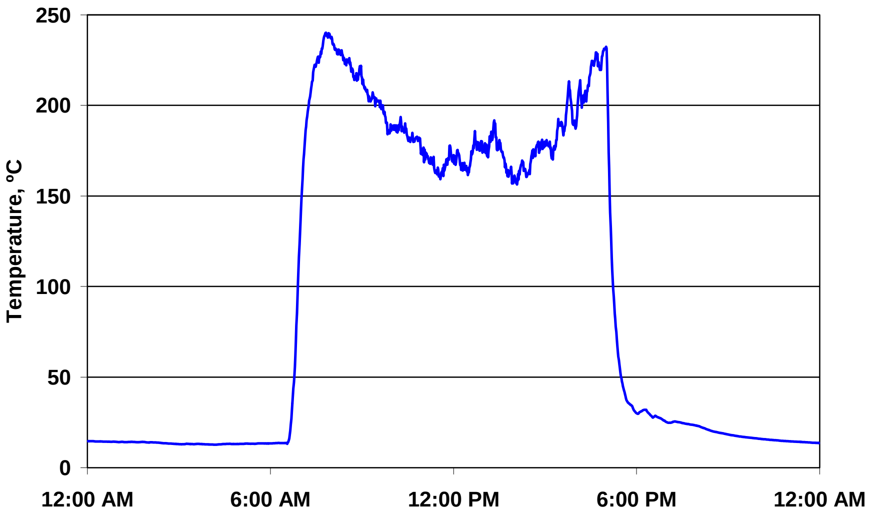
Click To Start Movie of Conductor Sag

Example run shows wind cools the conductor

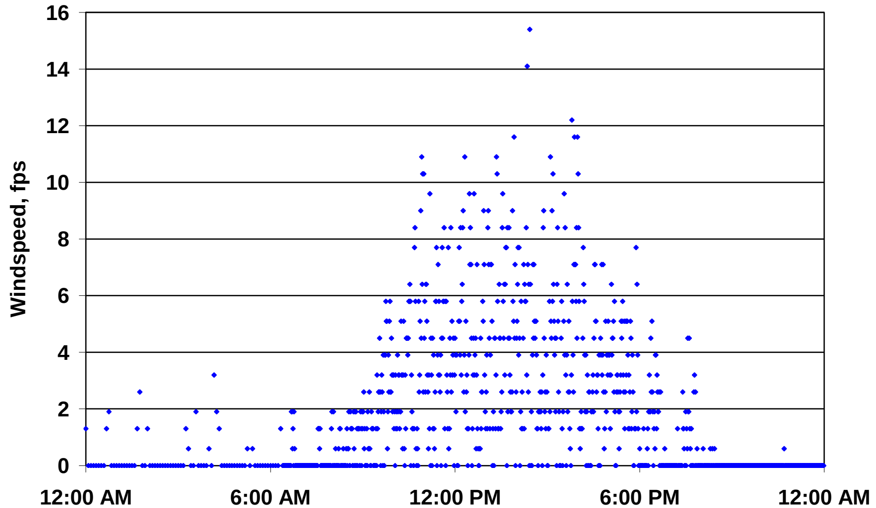
Current, 6/9/2003



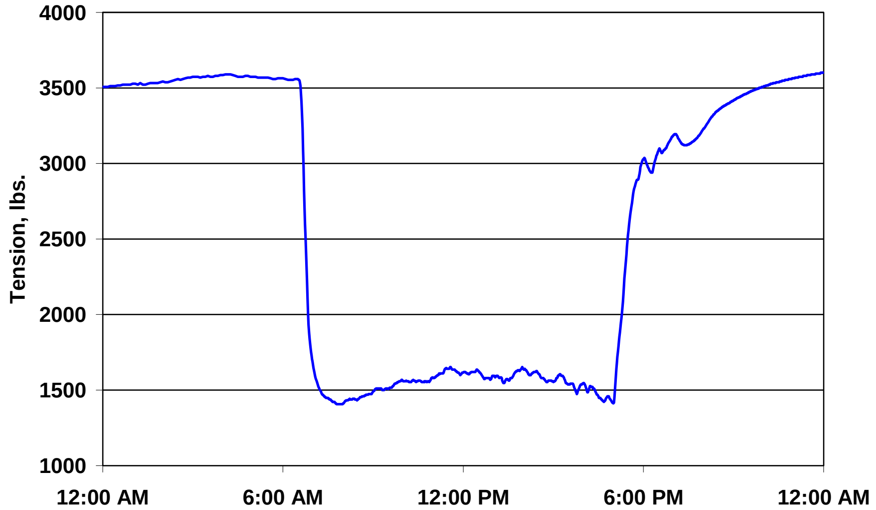
Average Conductor Temperature, 6/9/2003



Windspeed, 6/9/2003



Conductor Tension, 6/9/2003



Example of Thermal/Mechanical Cycling Run

Tuesday, Sept. 21, 2004

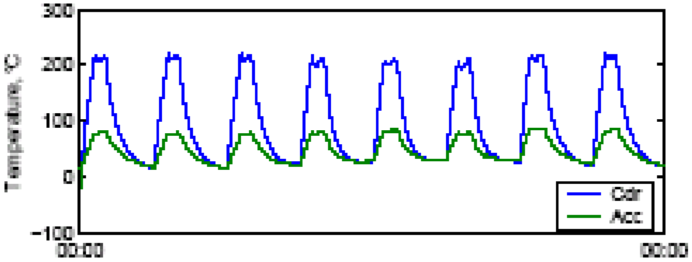


Fig. 1. Conductor Temperatures, Test Date: 2004/09/21 Tue

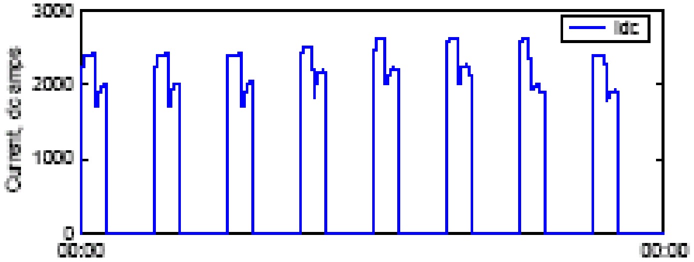


Fig. 2. dc Current, Test Date: 2004/09/21 Tue

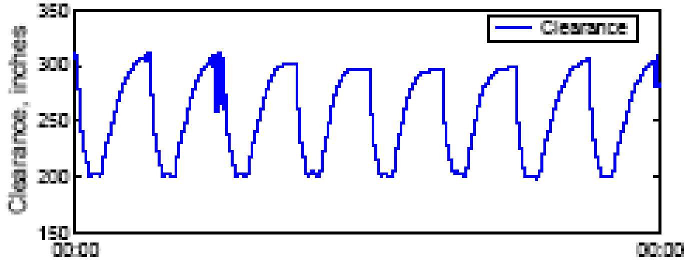


Fig. 3. Clearance from laser conductor, Test Date: 2004/09/21 Tue

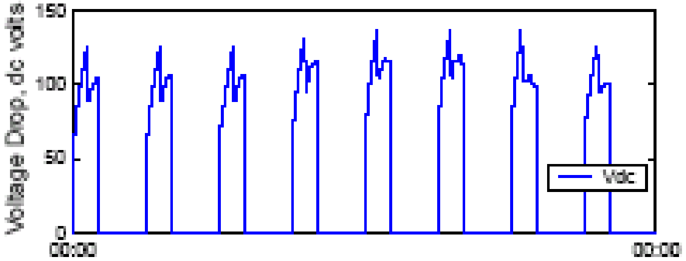


Fig. 4. dc Voltage Drop, Test Date: 2004/09/21 Tue

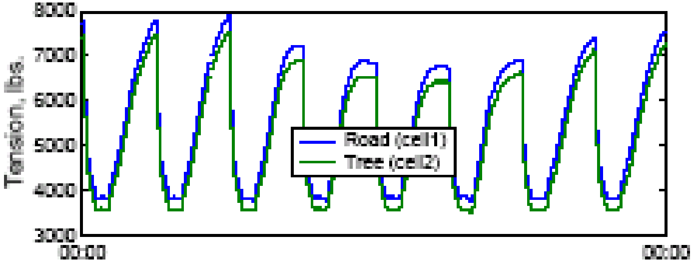


Fig. 5. Conductor Tension, Test Date: 2004/09/21 Tue

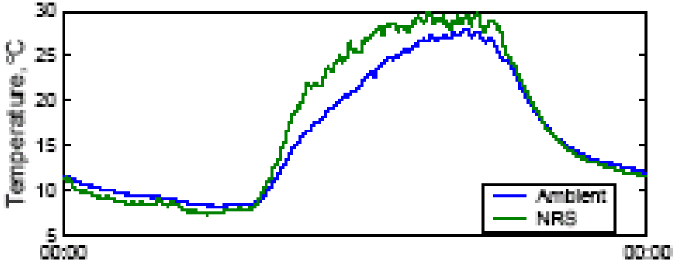


Fig. 6. Ambient & NRS Temperatures, Test Date: 2004/09/21 Tue

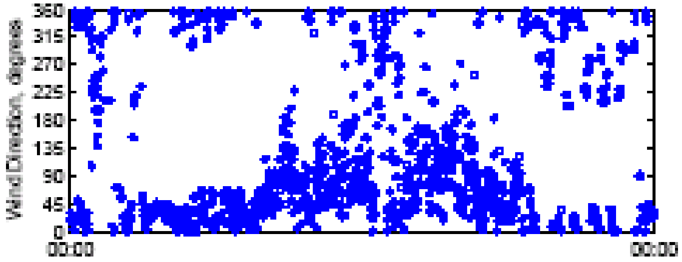


Fig. 7. Wind Direction, Test Date: 2004/09/21 Tue

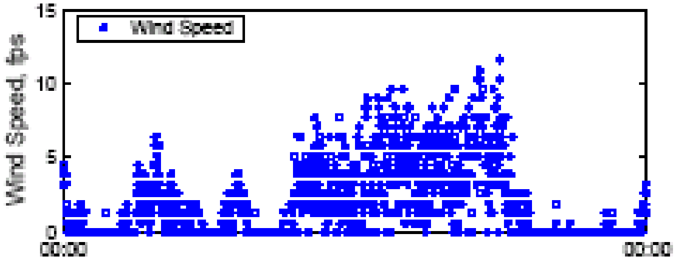
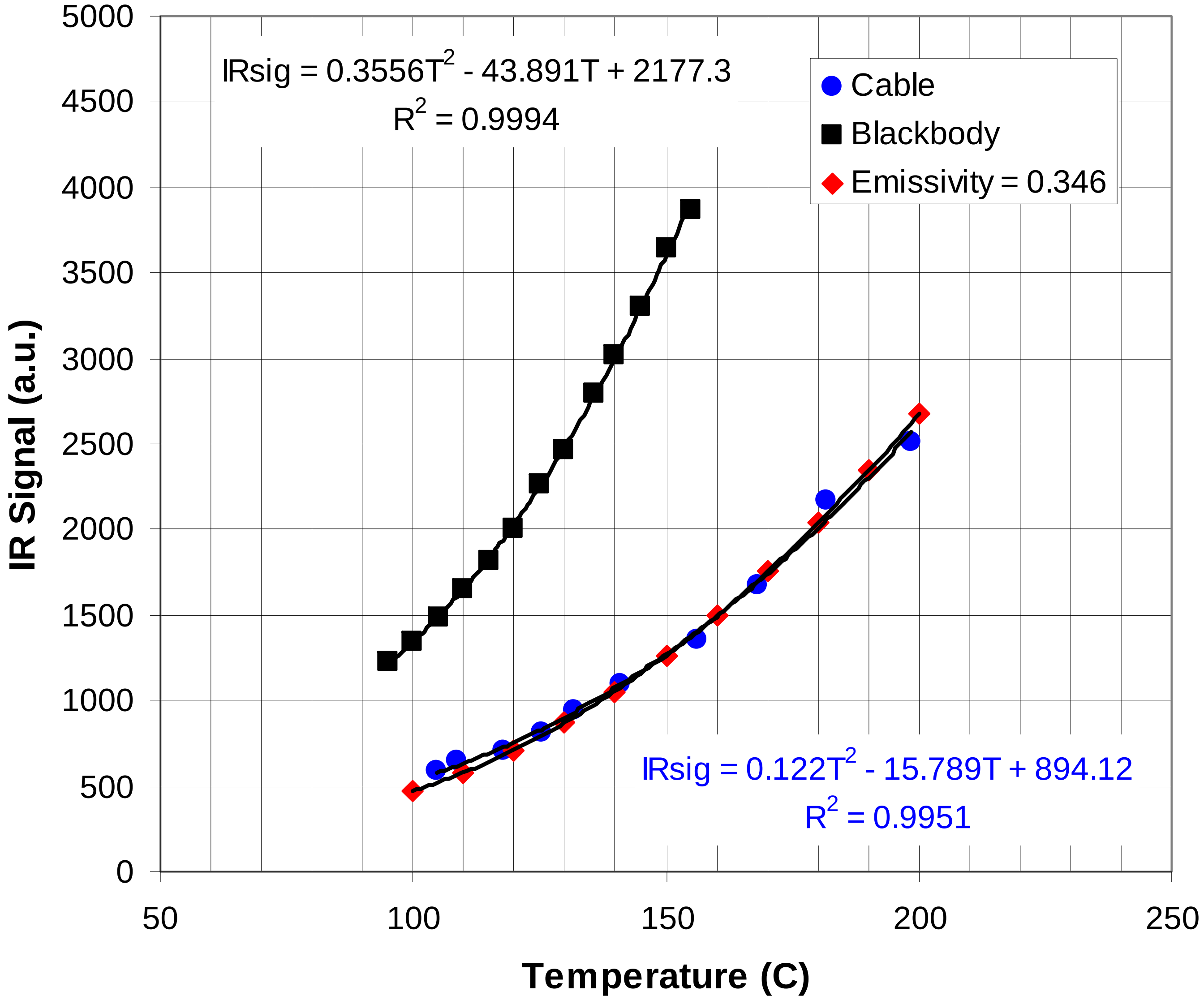


Fig. 8. Wind Speed, Test Date: 2004/09/21 Tue

IR Imaging Setup

One image per minute with Radiance-HS infrared camera equipped with a 100mm lens

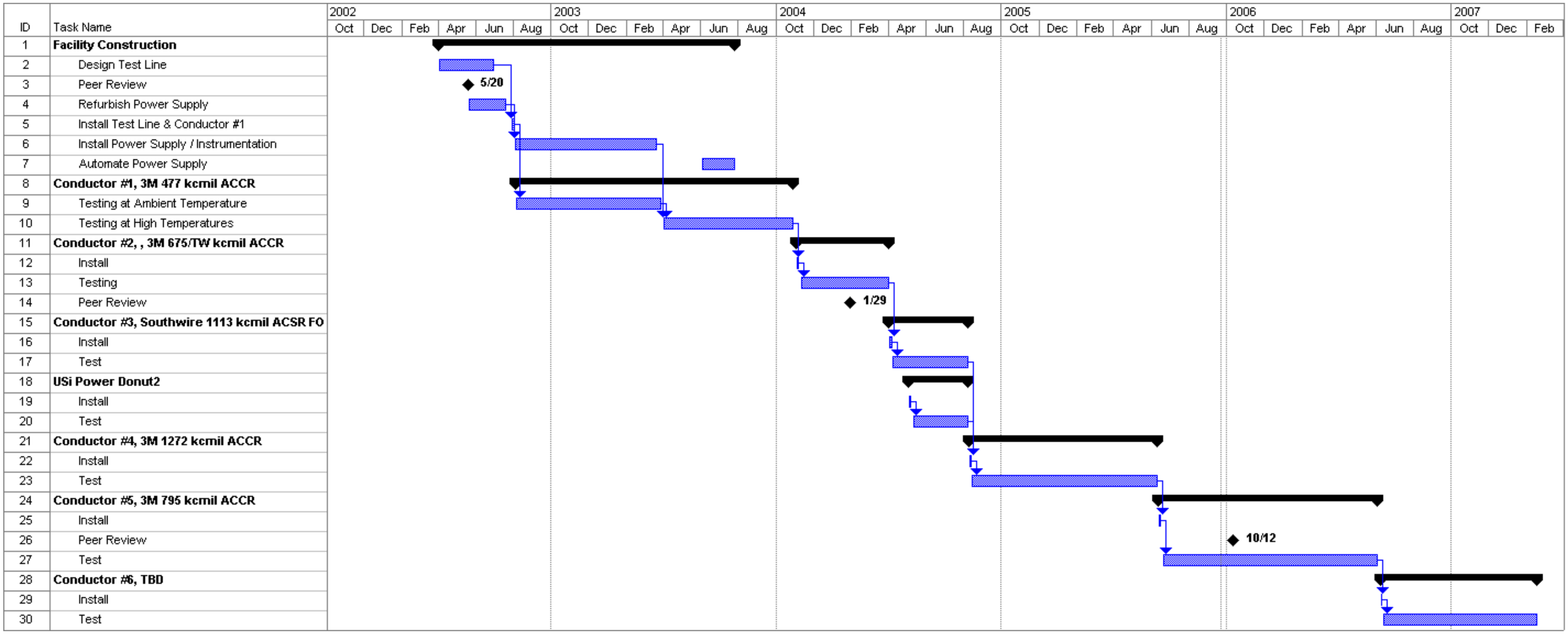
Blackbody Signal is multiplied by "emissivity" until it matches conductor signal



Thus far, five conductors and two conductor monitoring devices have been tested

1. **Aug. 2002 - Oct 2003 – 3M 477 kcmil ACCR**
2. **Nov. 2003 to Apr. 2004 – 3M 675 kcmil ACCR**
3. **Apr. 2004 to Aug. 2004 – Southwire 1113 kcmil ACSR with embedded optical fiber**
   - **Also tested, Power Donut2**
4. **Aug. 2004 to June 2005 – 3M 1272 kcmil ACCR**
5. **Installed June 2005 – 3M 795 kcmil ACCR**

Project Schedule



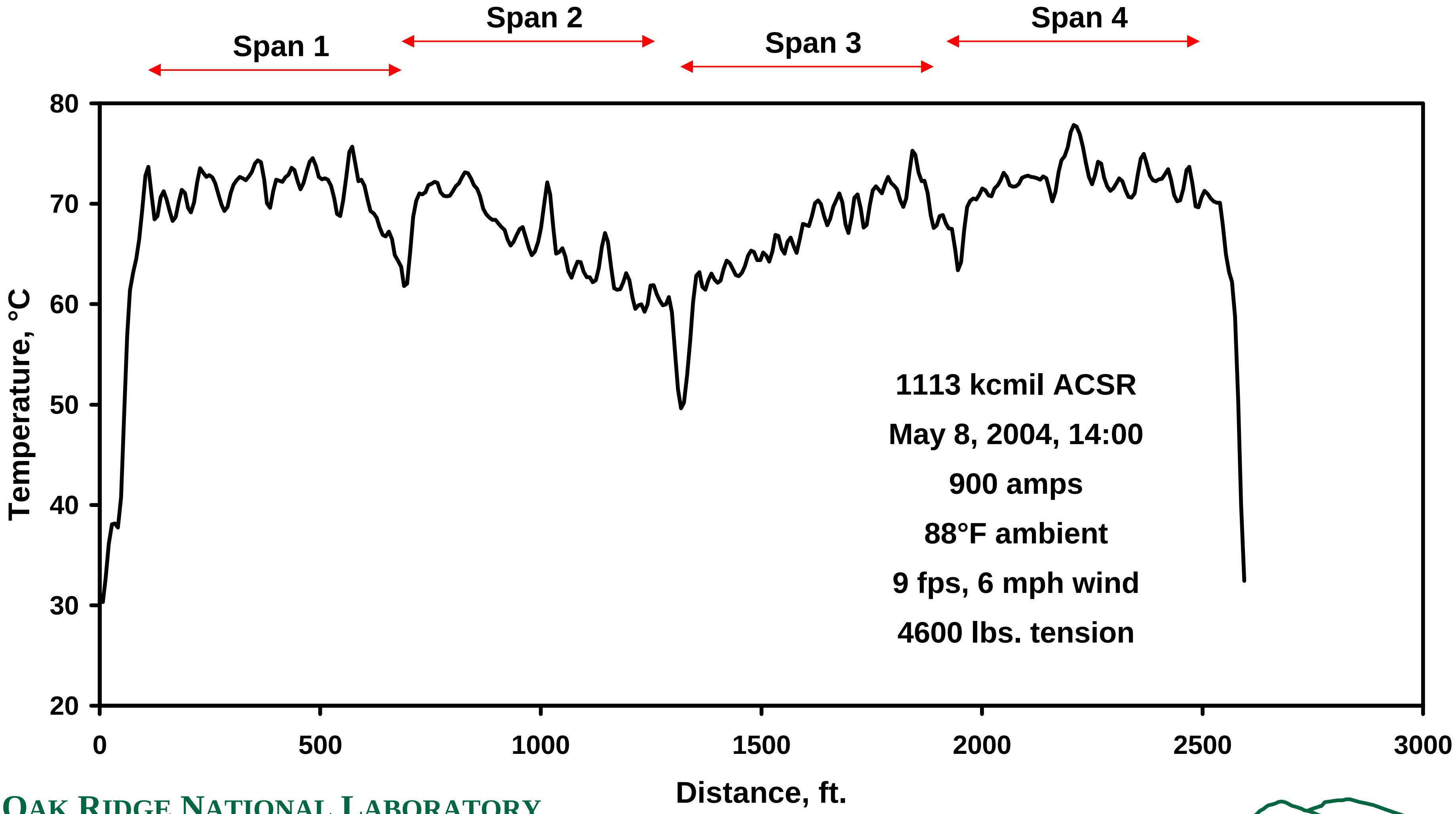
ID	Task Name
1	**Facility Construction**
2	Design Test Line
3	Peer Review
4	Refurbish Power Supply
5	Install Test Line & Conductor #1
6	Install Power Supply / Instrumentation
7	Automate Power Supply
8	**Conductor #1, 3M 477 kcmil ACCR**
9	Testing at Ambient Temperature
10	Testing at High Temperatures
11	**Conductor #2, , 3M 675/TW kcmil ACCR**
12	Install
13	Testing
14	Peer Review
15	**Conductor #3, Southwire 1113 kcmil ACSR FO**
16	Install
17	Test
18	**USi Power Donut2**
19	Install
20	Test
21	**Conductor #4, 3M 1272 kcmil ACCR**
22	Install
23	Test
24	**Conductor #5, 3M 795 kcmil ACCR**
25	Install
26	Peer Review
27	Test
28	**Conductor #6, TBD**
29	Install
30	Test

FY 2002 **FY 2003** **FY 2004** **FY 2005** **FY 2006**

Fiber Optic Transmission Conductor (FOTC) Measure Temperature Along Length

- **Embed optical fibers in standard bare overhead conductors**
  - **Optical fiber allows temperature measurement every 2 meters along length of line**
  - **Temperature measurement uses the physical properties of the optical fiber (Raman backscattering)**
  - **Commercially available equipment used to measure temperature profile**
- **Manufactured by Southwire Company**
- **Testing and Field Demonstration**
  - **Small scale verification test at ORNL in 2001**
  - **Field tested at ComEd, Feb. 2002 to present on 230 kV line**
  - **Outdoor verification test at ORNL, Apr. – Aug. 2004**

FOTC - Example Temperature Profile



1113 kcmil ACSR

May 8, 2004, 14:00

900 amps

88°F ambient

9 fps, 6 mph wind

4600 lbs. tension

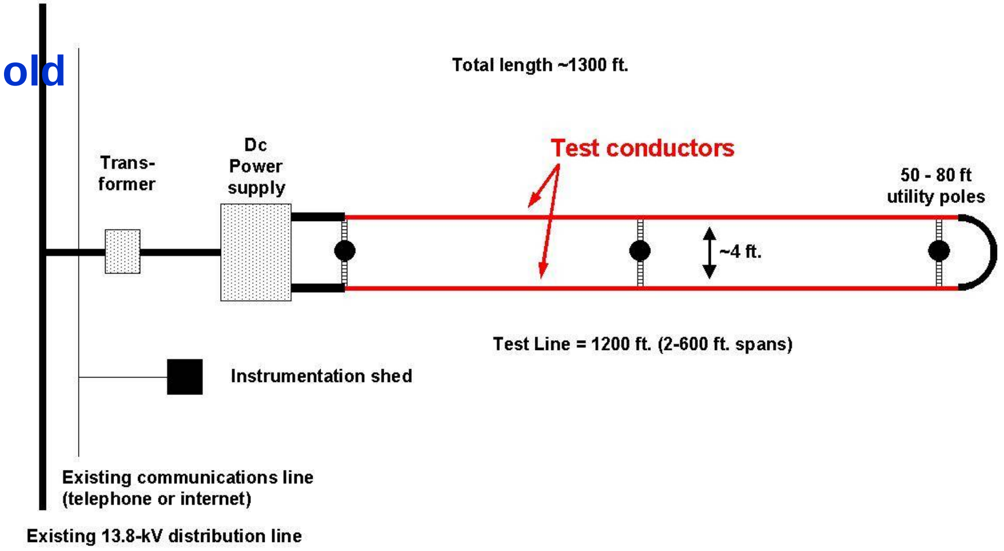
Real-Time Transmission Line Monitoring

Wireless Communication to Ground Station

- **Power Donut2**
  - completely self contained and self powered
  - Completely redesigned with new electronics and communications options
  - attaches to the conductor using hot stick
  - measures current, voltage, MW, MVars, MWh, conductor temperature, conductor inclination
  - stores data on board
  - transmits data continuously or on demand
- **Testing at ORNL to gather operating data on a new measurement feature**
  - Measuring conductor incline to determine conductor sag
- **Line Rating Systems**
- **Manufactured by USi, Armonk, NY**
  - www.usi-power.com

Facility Capabilities

- **Testing Capabilities**
  - Controlled current or temperature testing
  - Conductor and accessories
  - Up to 300°C
- **Example tests**
  - Constant Current or Constant Temperature
  - Thermal / Mechanical Cycling
  - Current / Temperature Ramp
  - Current / Temperature Steps and Hold
- **Capabilities**
  - 2400 feet of conductor
  - 2 – 600 foot spans
  - Low Voltage, 0 to 400 Vdc
  - High Current, up to 5,000 Adc



Measurements

- Conductor/accessory temperature
  - Direct contact on surface or conductor core
  - 128 thermocouples available
  - 40 to 80 thermocouples used for testing
- Applied current and voltage
  - Measured by power supply
- Conductor sag
  - Laser at mid-span #1 on tree side circuit
- Conductor tension
  - Load cells on both circuits
- Weather
  - Ambient temperature, wind speed, wind direction
  - Conductor net radiation sensor
- PC-based data acquisition system
  - 10 second polling
  - 1 minute data archive

Project Summary
Transmission Test Facility

- **Fulfilling a programmatic goal defined in a recommendation of the National Transmission Grid Study**
- **Provides a unique transmission conductor testing facility to augment utility field tests and demonstrations**
- **Each conductor test undertaken in collaboration with industrial partner**

Laser at mid-span measure conductor sag

Questions

Contact Information

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  - kisnerra@ornl.gov

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  - (865) 574-9338 Fax
  - rizydt@ornl.gov

- **John P. Stovall**
  - (865) 574-5198 Voice
  - (865) 574-9338 Fax
  - stovalljp@ornl.gov

Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831

Appendix C.4

DOE Peer Review Presentation – October 17, 2006

Power Line Conductor Accelerated Testing

U.S. Department of Energy
Visualization and Controls Program
Peer Review

John P. Stovall
Oak Ridge National Laboratory

ORNL Project Team
D. Tom Rizy
Roger A. Kisner
John P. Stovall

Marriott Crystal City at Reagan National Airport
1999 Jefferson Davis Highway
Arlington, VA, 22202

October 17, 2006

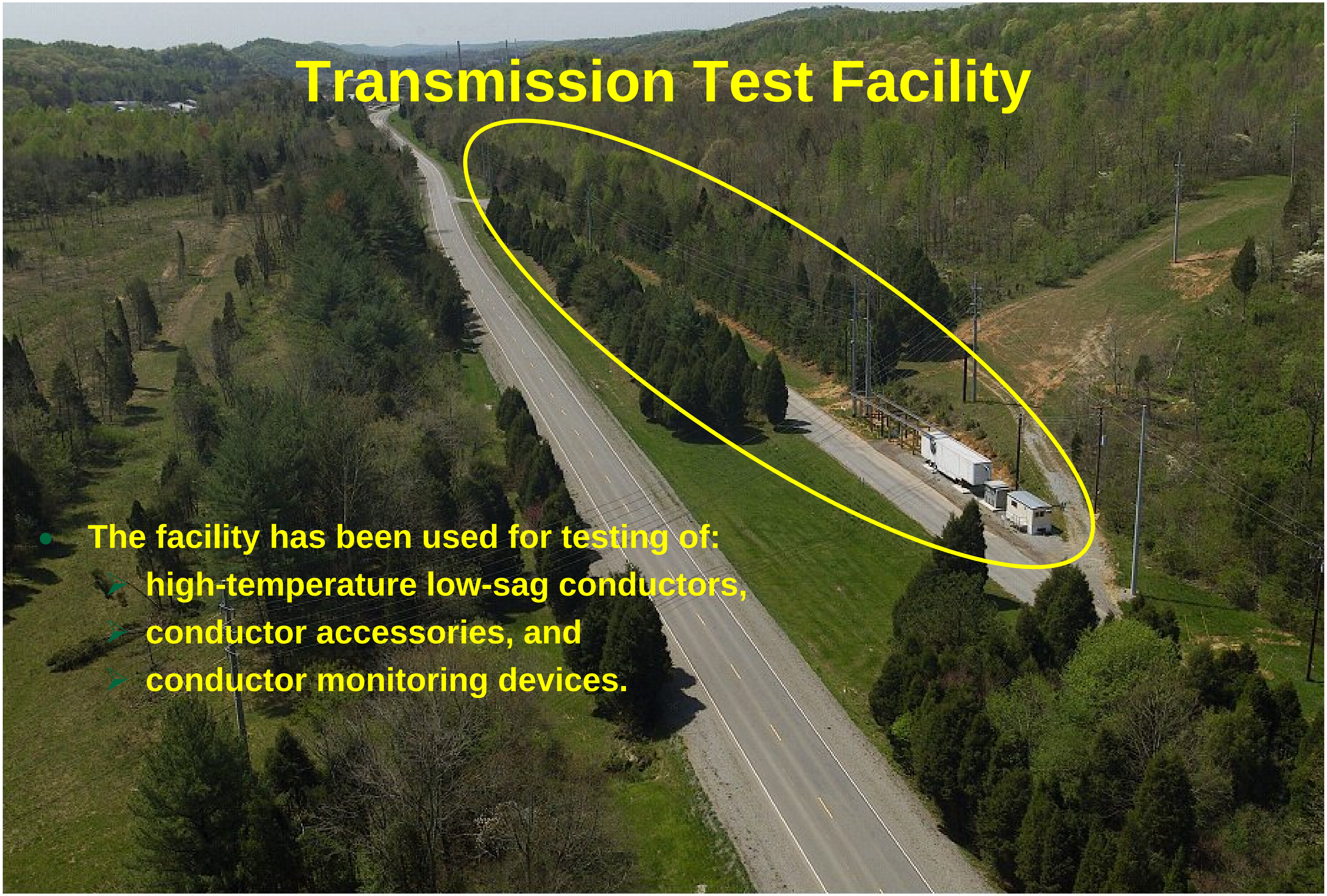
National Transmission Grid Study

One of the 51 Recommendations

"DOE will develop national transmission-technology testing facilities that encourage partnering with industry to demonstrate advanced technologies in controlled environments.

Working with TVA, DOE will create an industry cost-shared transmission line testing center at DOE 's Oak Ridge National Laboratory (with at least a 50 percent industry cost share).*"

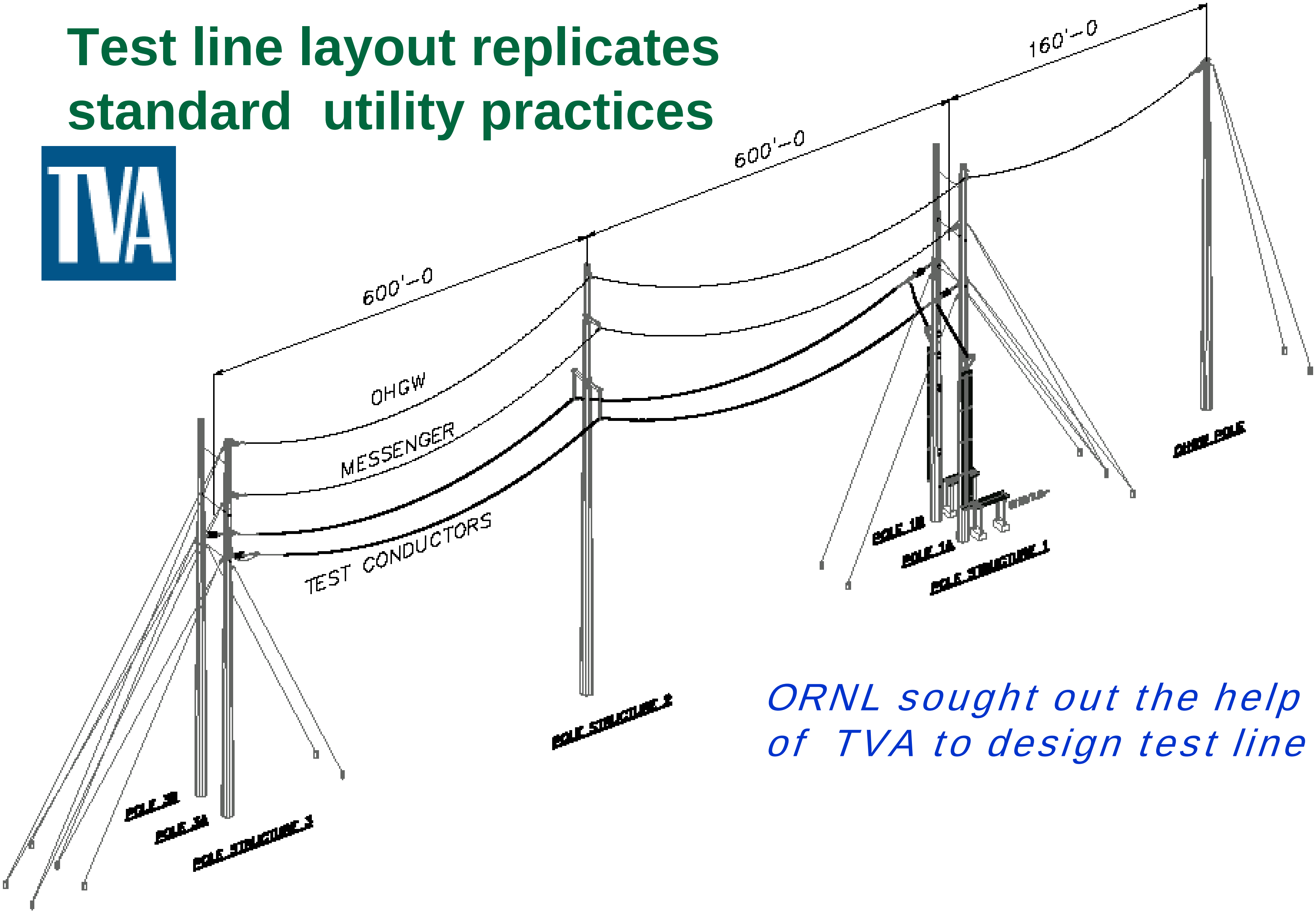
*National Transmission Grid Study, U.S. DOE, May 2002 www.ntgs.doe.gov



Transmission Test Facility

- The facility has been used for testing of:
  - high-temperature low-sag conductors,
  - conductor accessories, and
  - conductor monitoring devices.

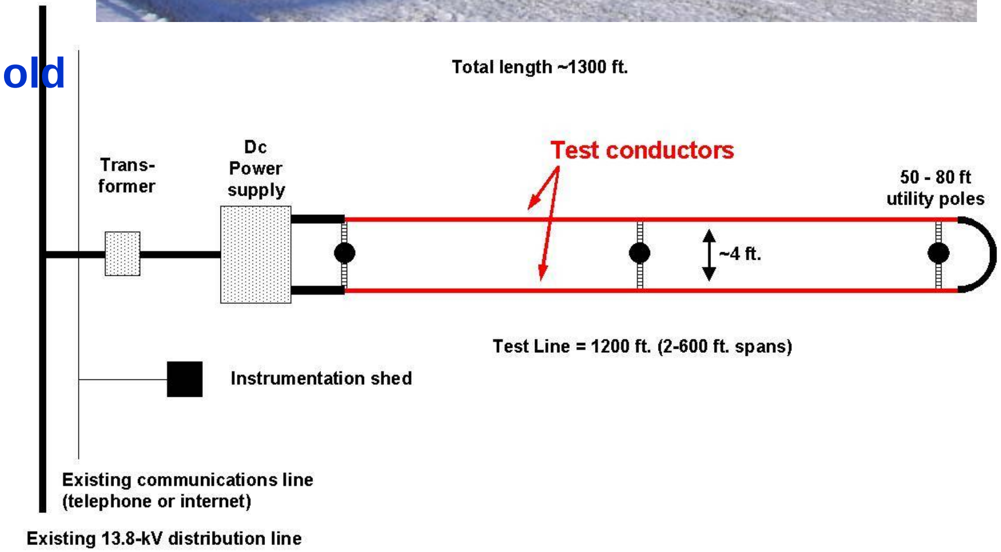
Test line layout replicates standard utility practices



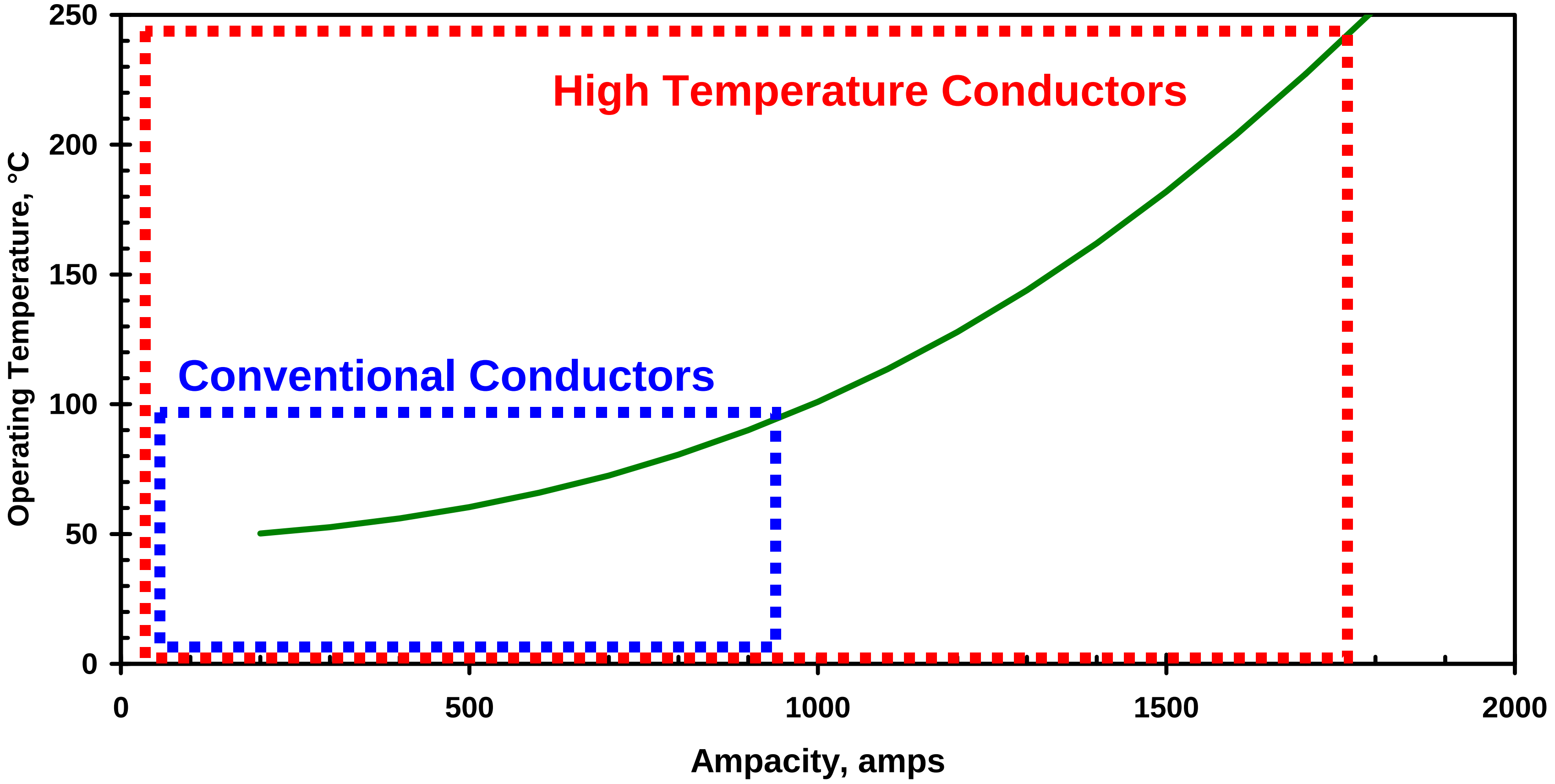
ORNL sought out the help of TVA to design test line

Facility Capabilities Are Unique

- **Testing Capabilities**
  - Controlled current or temperature testing
  - Conductor and accessories
  - Up to 300ºC
- **Example tests**
  - Constant Current or Constant Temperature
  - Thermal / Mechanical Cycling
  - Current / Temperature Ramp
  - Current / Temperature Steps and Hold
- **Capabilities**
  - 2400 feet of conductor
  - 2 – 600 foot spans
  - Low Voltage, 0 to 400 Vdc
  - High Current, up to 5,000 Adc

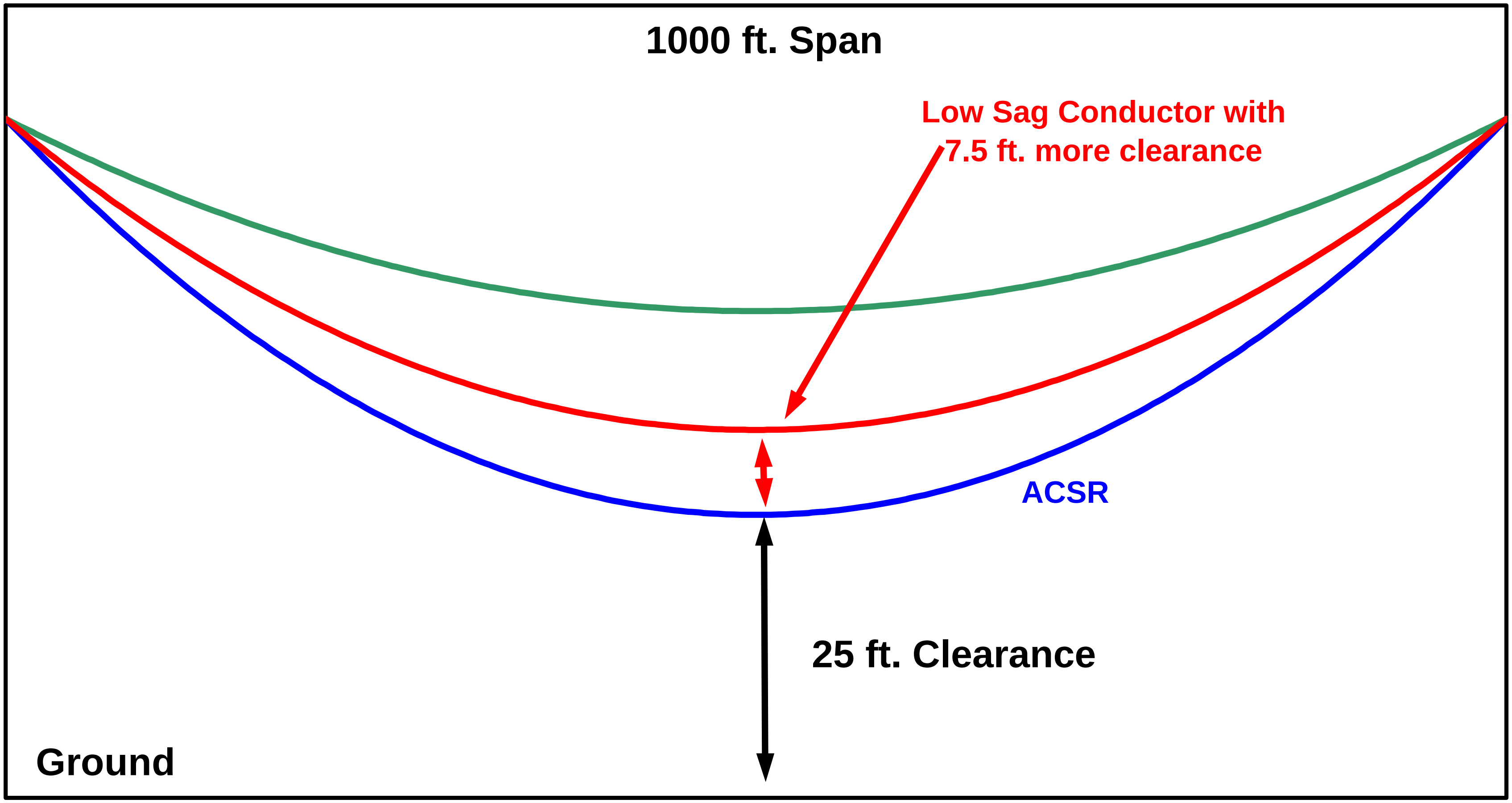


Benefit of higher operating temperatures is higher current rating

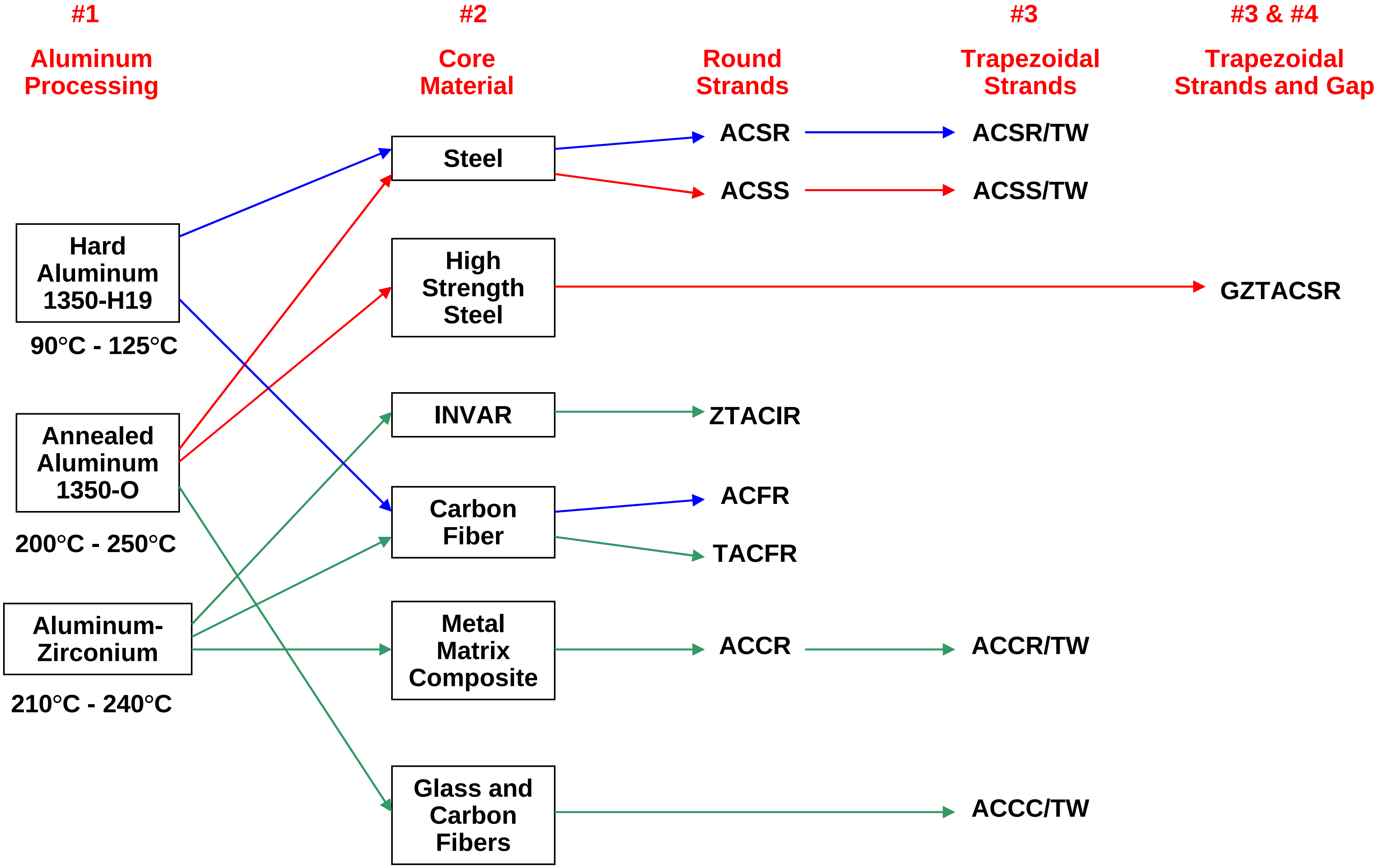


Need to test / verify new conductors over entire operating range

Benefit of a conductor that thermally expands at one-half the rate of ACSR is lower sag



Conductor Road Map



#1 **Aluminum Processing**

#2 **Core Material**

Round Strands

#3 **Trapezoidal Strands**

#3 & #4 **Trapezoidal Strands and Gap**

Hard Aluminum 1350-H19

90°C - 125°C

Annealed Aluminum 1350-O

200°C - 250°C

Aluminum-Zirconium

210°C - 240°C

Steel

High Strength Steel

INVAR

Carbon Fiber

Metal Matrix Composite

Glass and Carbon Fibers

ACSR → **ACSR/TW**

ACSS → **ACSS/TW**

GZTACSR

ZTACIR

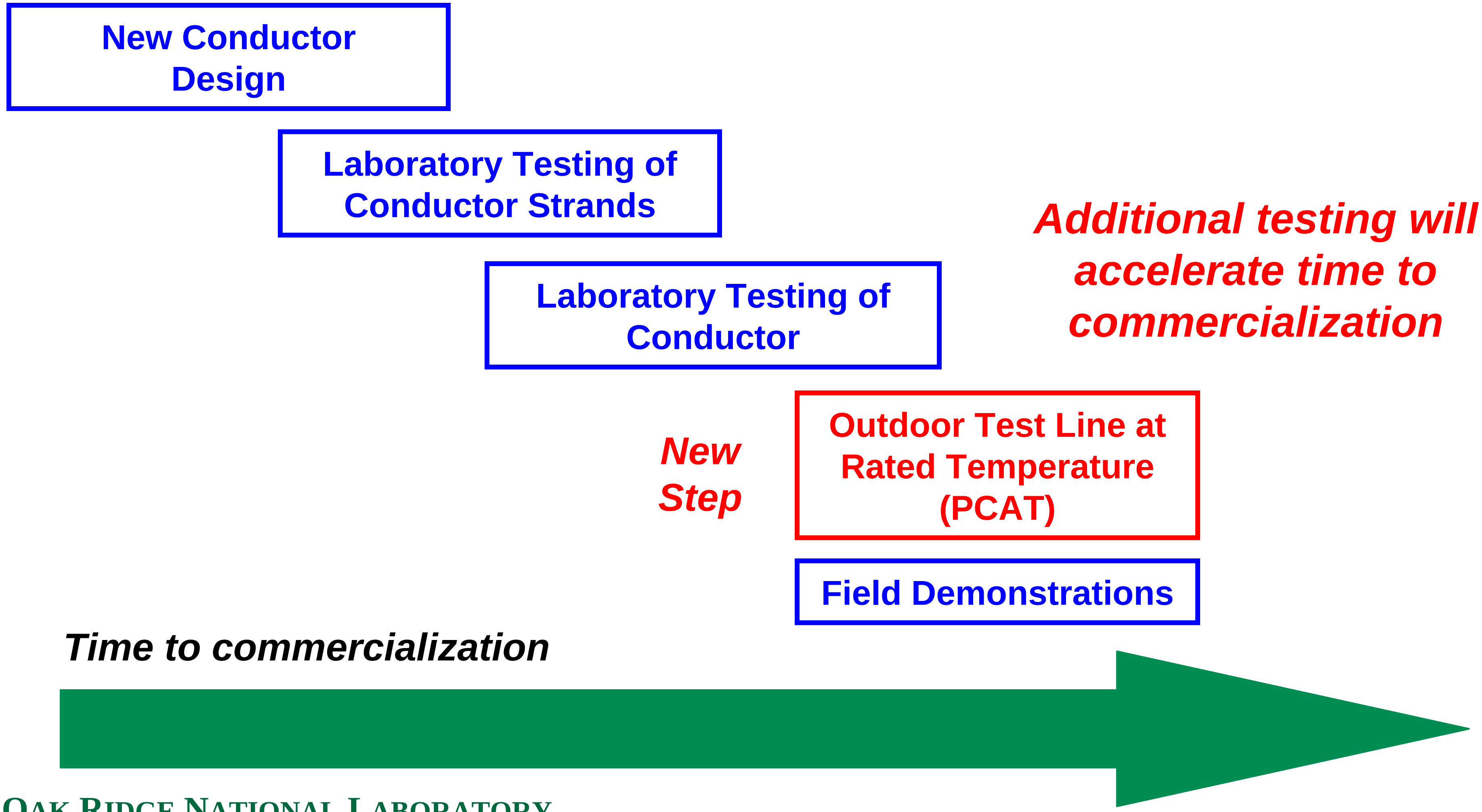
ACFR

TACFR

ACCR → **ACCR/TW**

ACCC/TW

Bringing a New Conductor to Market



New Conductor Design

Laboratory Testing of Conductor Strands

Laboratory Testing of Conductor

New Step

Outdoor Test Line at Rated Temperature (PCAT)

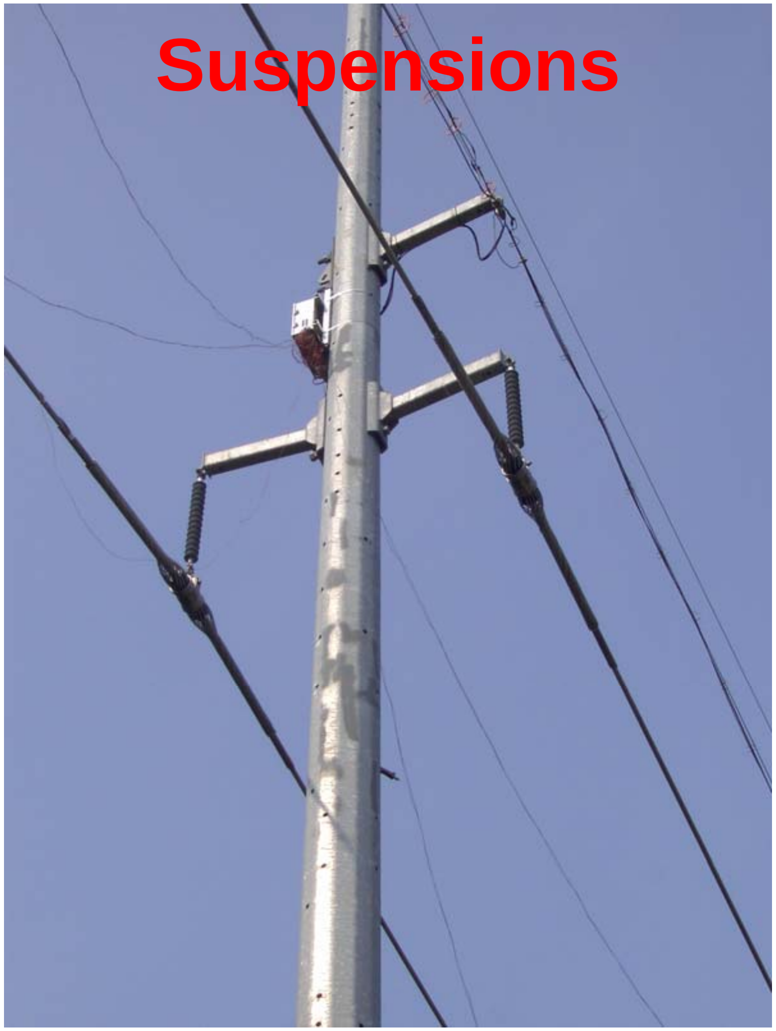
Field Demonstrations

Time to commercialization

Additional testing will accelerate time to commercialization

Structure #1 & #3
Dead-Ends and Jumpers

Structure #2 and Mid-Spans



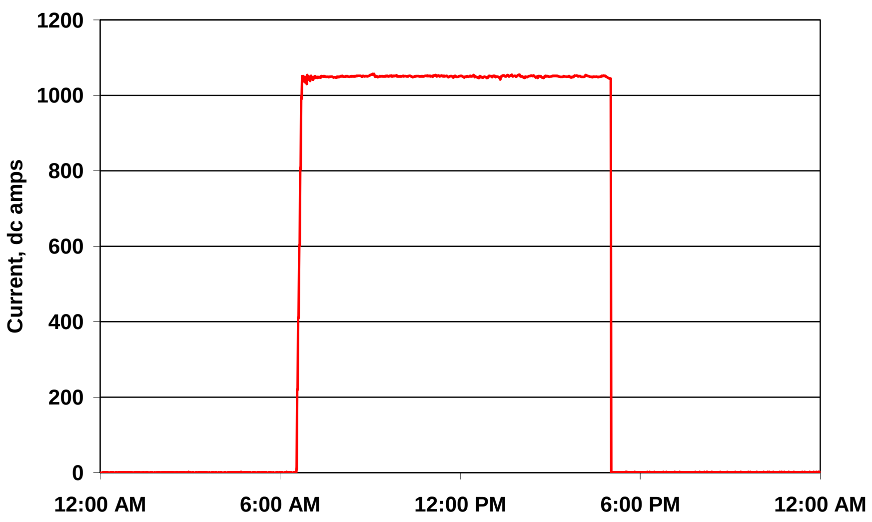
Splices at Mid-Spans

Installation of test conductor and accessories takes a transmission line construction crew three or four days

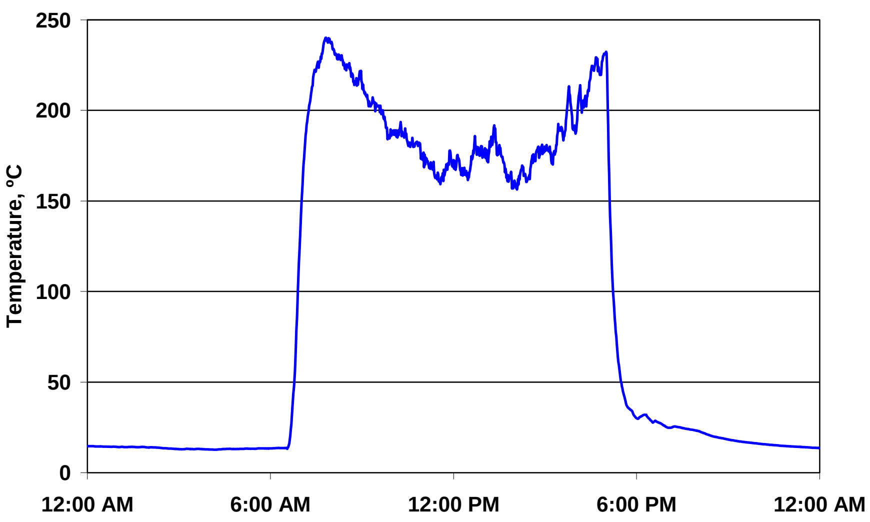
Test Conductors Are Installed Using Standard Equipment

Click To Start Movie of Conductor Sag

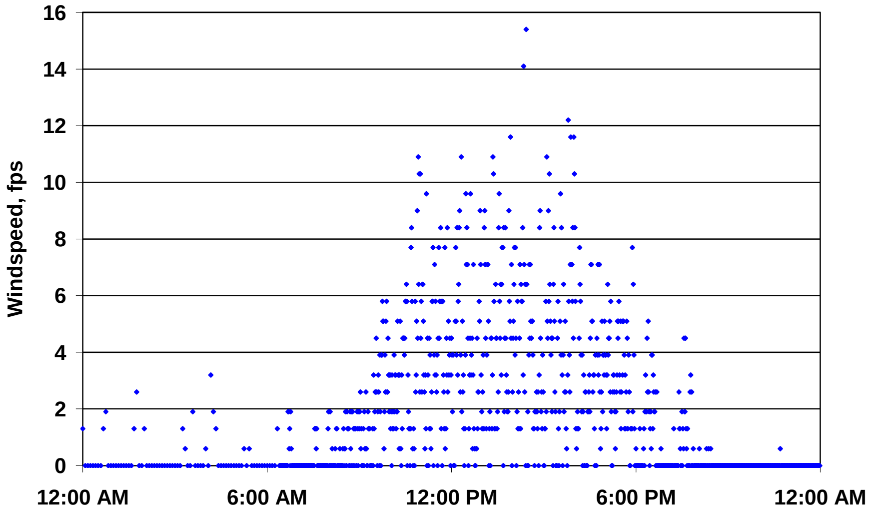
Example run shows wind cools the conductor



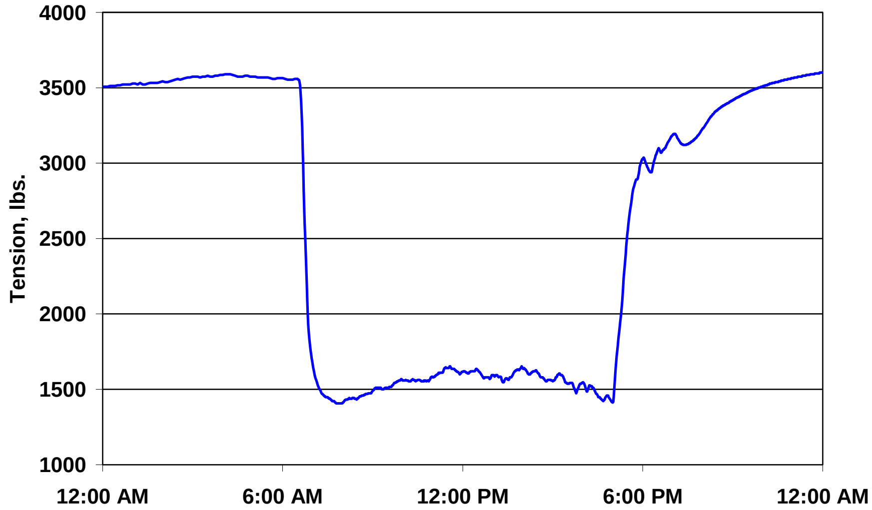
Current



Average Conductor Temperature

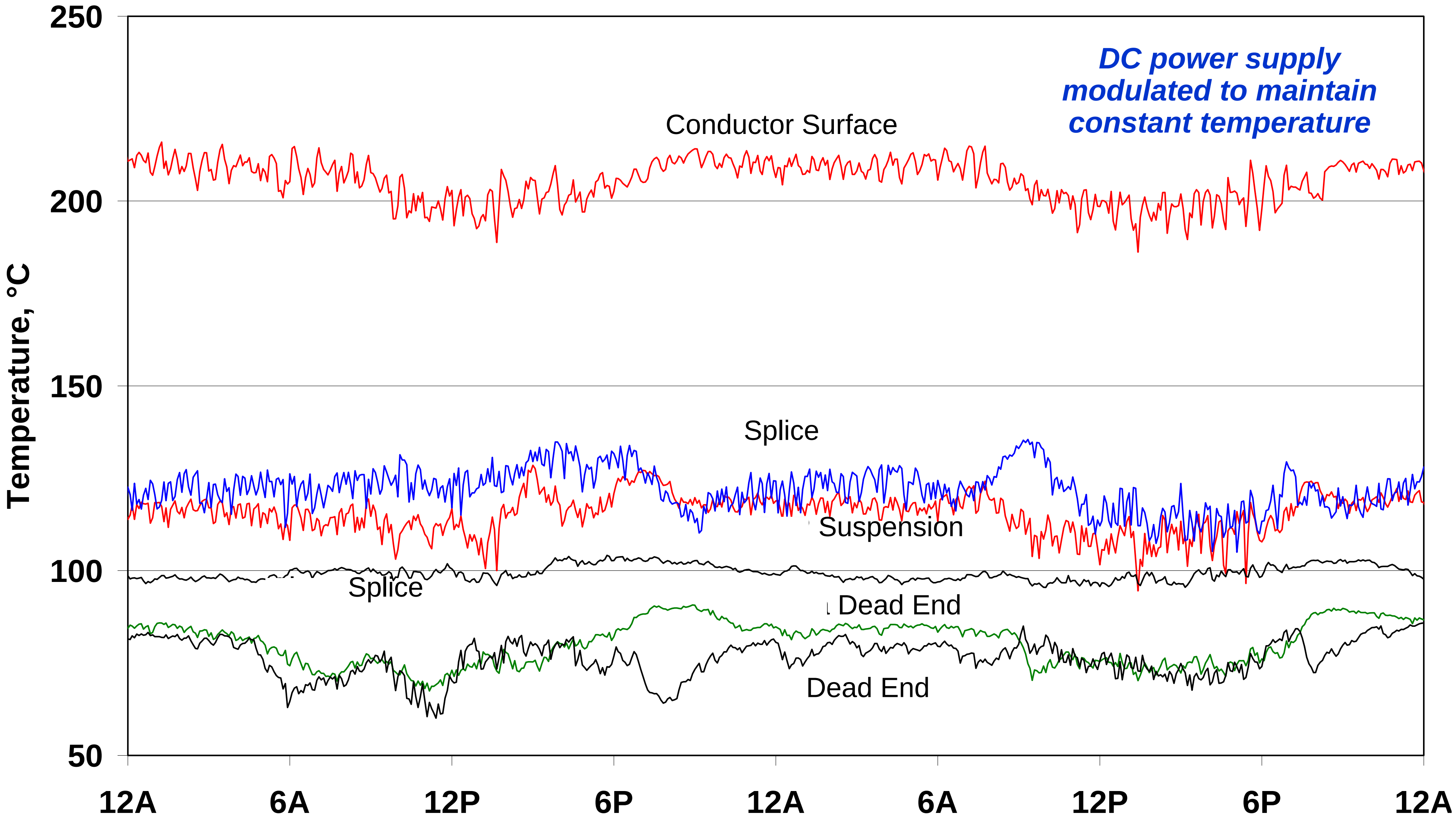


Windspeed



Conductor Tension

Conductor and accessory temperatures can be measured because this is a test line



DC power supply modulated to maintain constant temperature

All key parameters are being measured

- **Conductor/accessory temperature**
  - **Direct contact on surface or conductor core**
  - **128 thermocouples available**
  - **40 to 80 thermocouples used for testing**
- **Applied current and voltage**
  - **Measured by power supply**
- **Conductor sag**
  - **Laser at mid-span #1 on tree side circuit**
- **Conductor tension**
  - **Load cells on both circuits**
- **Weather**
  - **Ambient temperature, wind speed, wind direction**
  - **Conductor net radiation sensor**
- **PC-based data acquisition system**
  - **10 second polling**
  - **1 minute data archive**

Thermal/mechanical cycling can simulate many years of operation

Fig. 1. Conductor Temperatures, Test Date: 2004/09/21 Tue

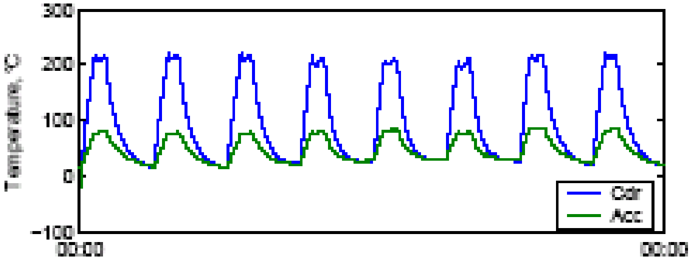


Fig. 2. dc Current, Test Date: 2004/09/21 Tue

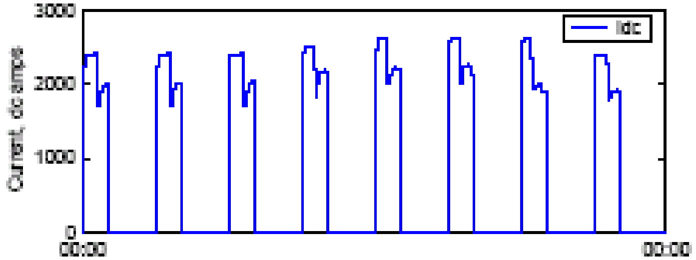


Fig. 3. Clearance from laser conductor, Test Date: 2004/09/21 Tue

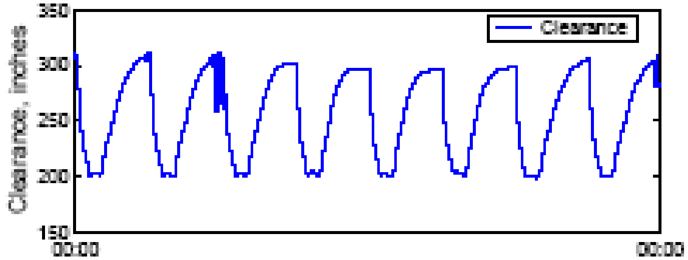


Fig. 4. dc Voltage Drop, Test Date: 2004/09/21 Tue

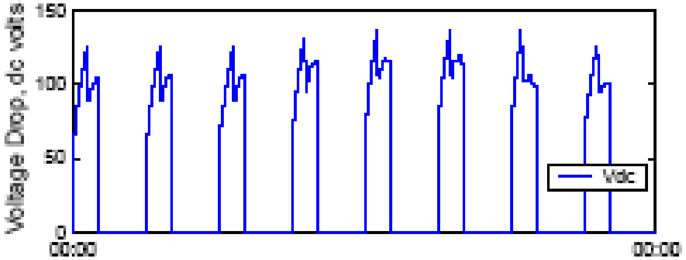


Fig. 5. Conductor Tension, Test Date: 2004/09/21 Tue

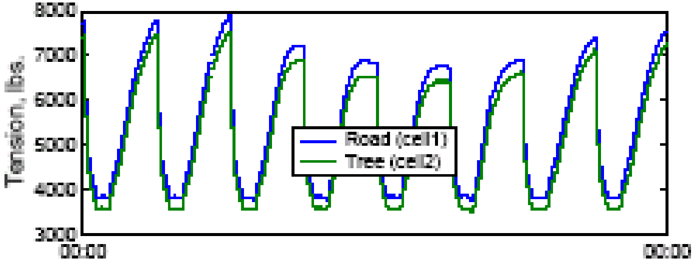


Fig. 6. Ambient & NRS Temperatures, Test Date: 2004/09/21 Tue

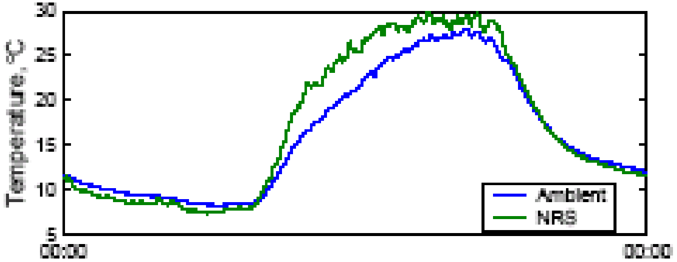


Fig. 7. Wind Direction, Test Date: 2004/09/21 Tue

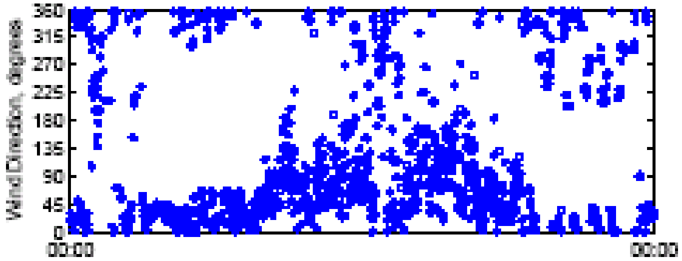
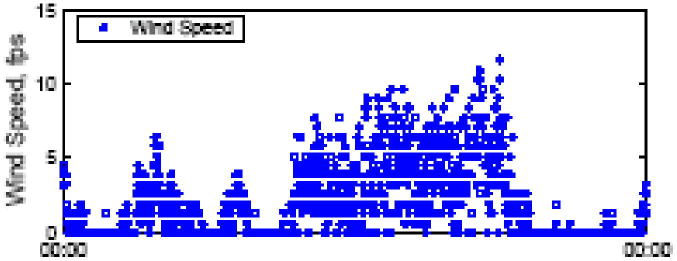
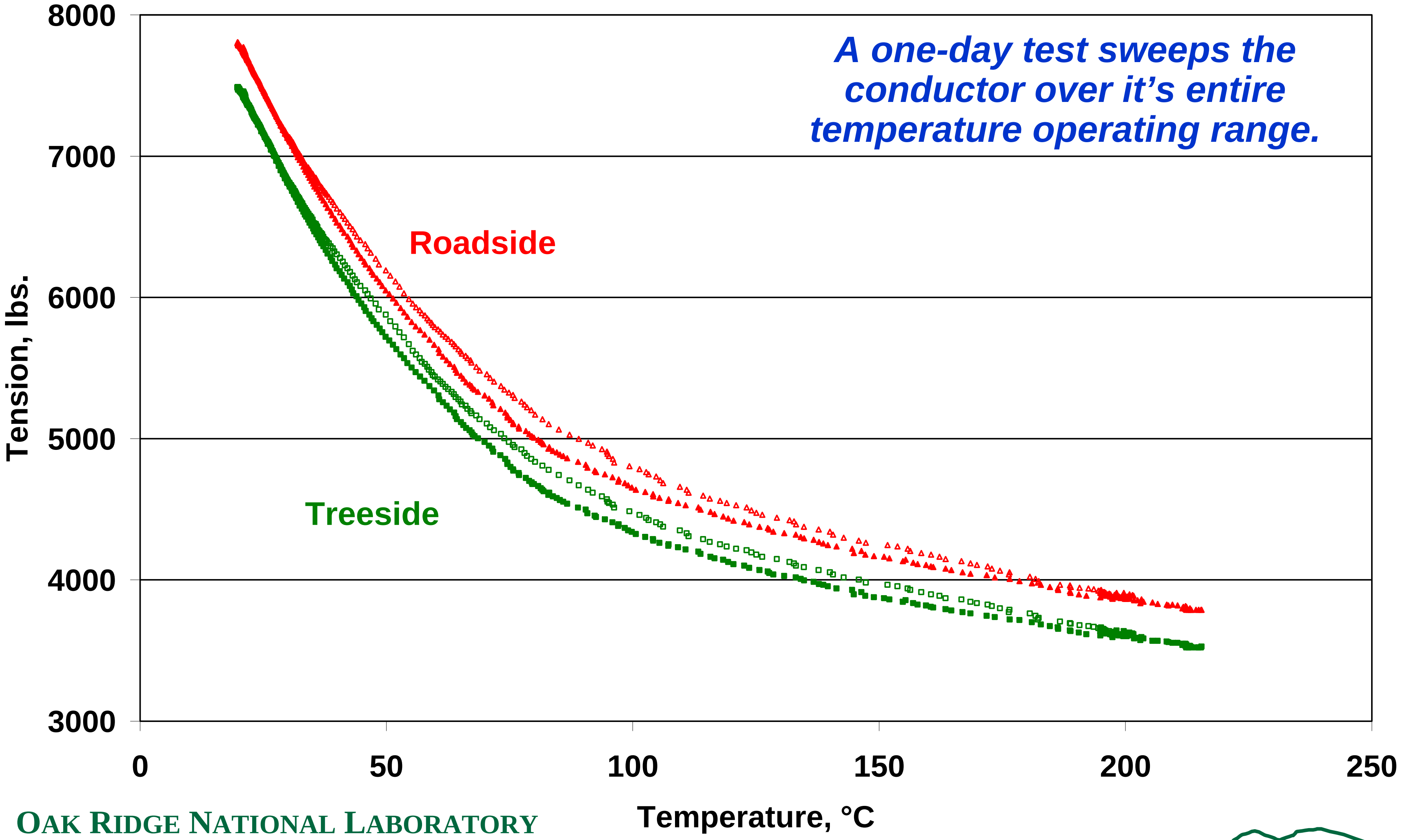


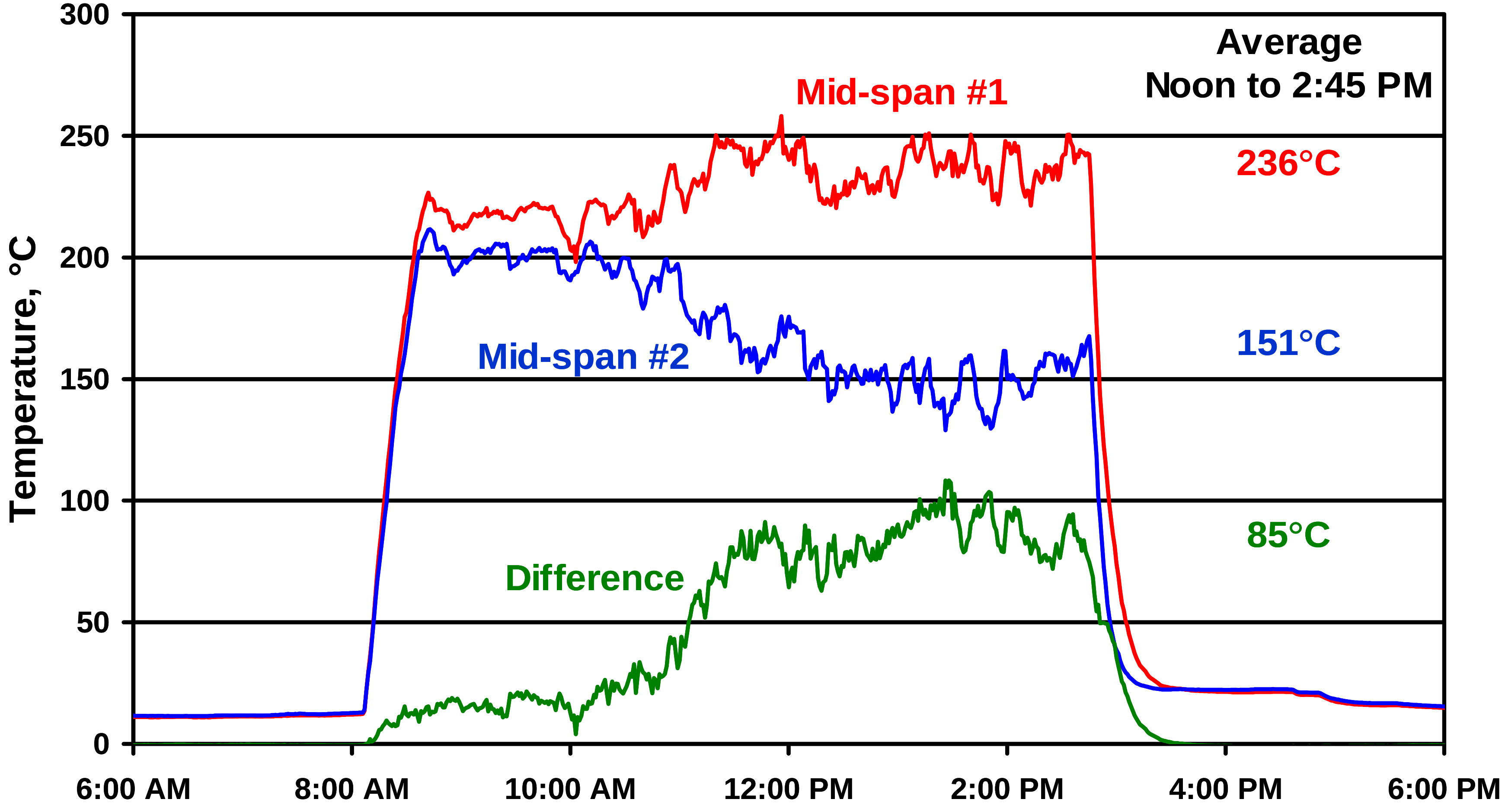
Fig. 8. Wind Speed, Test Date: 2004/09/21 Tue



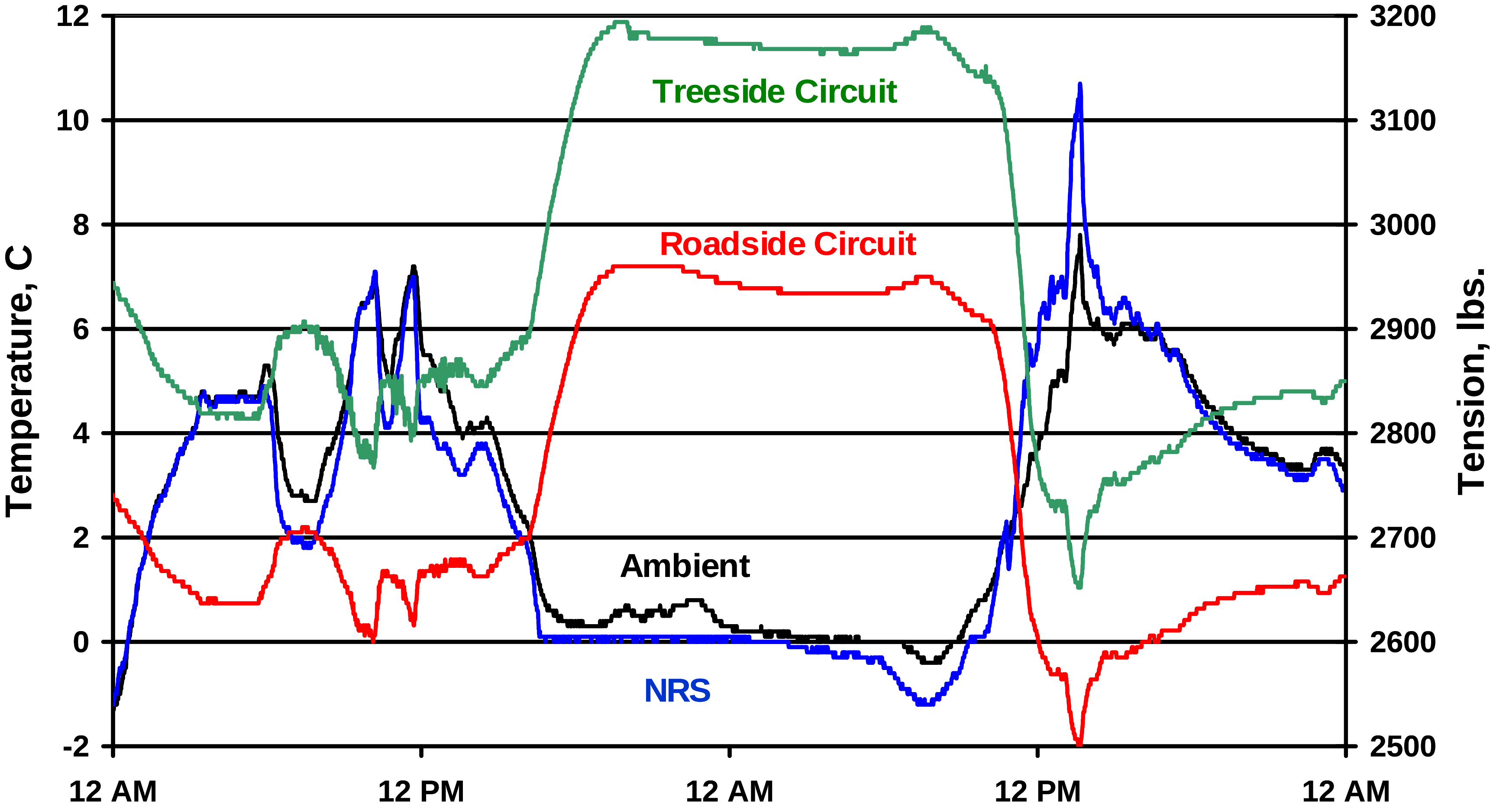
Knee-point test shows transition of tension



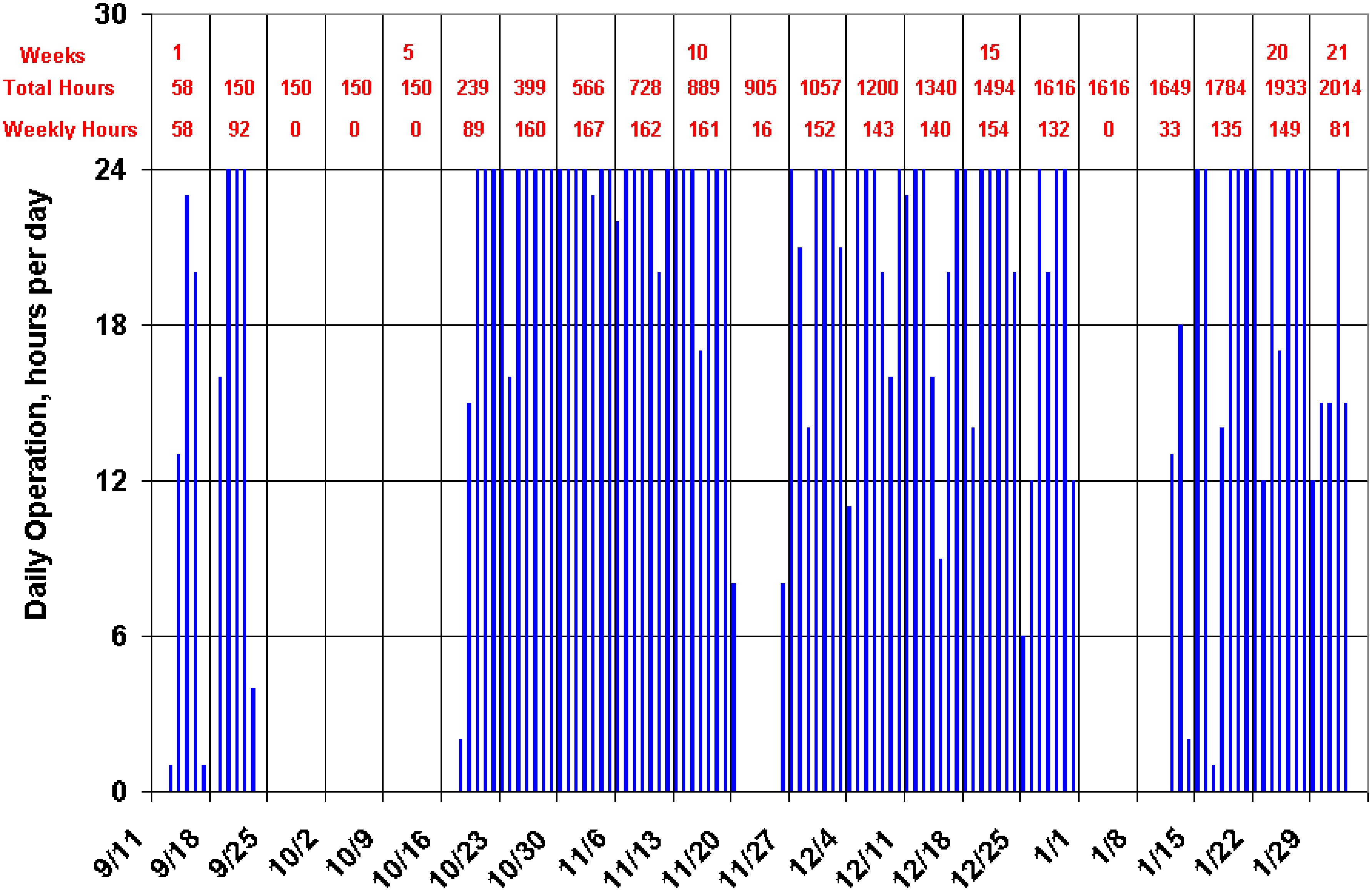
Axial Temperature Difference
85°C between 600 ft. Mid-Spans



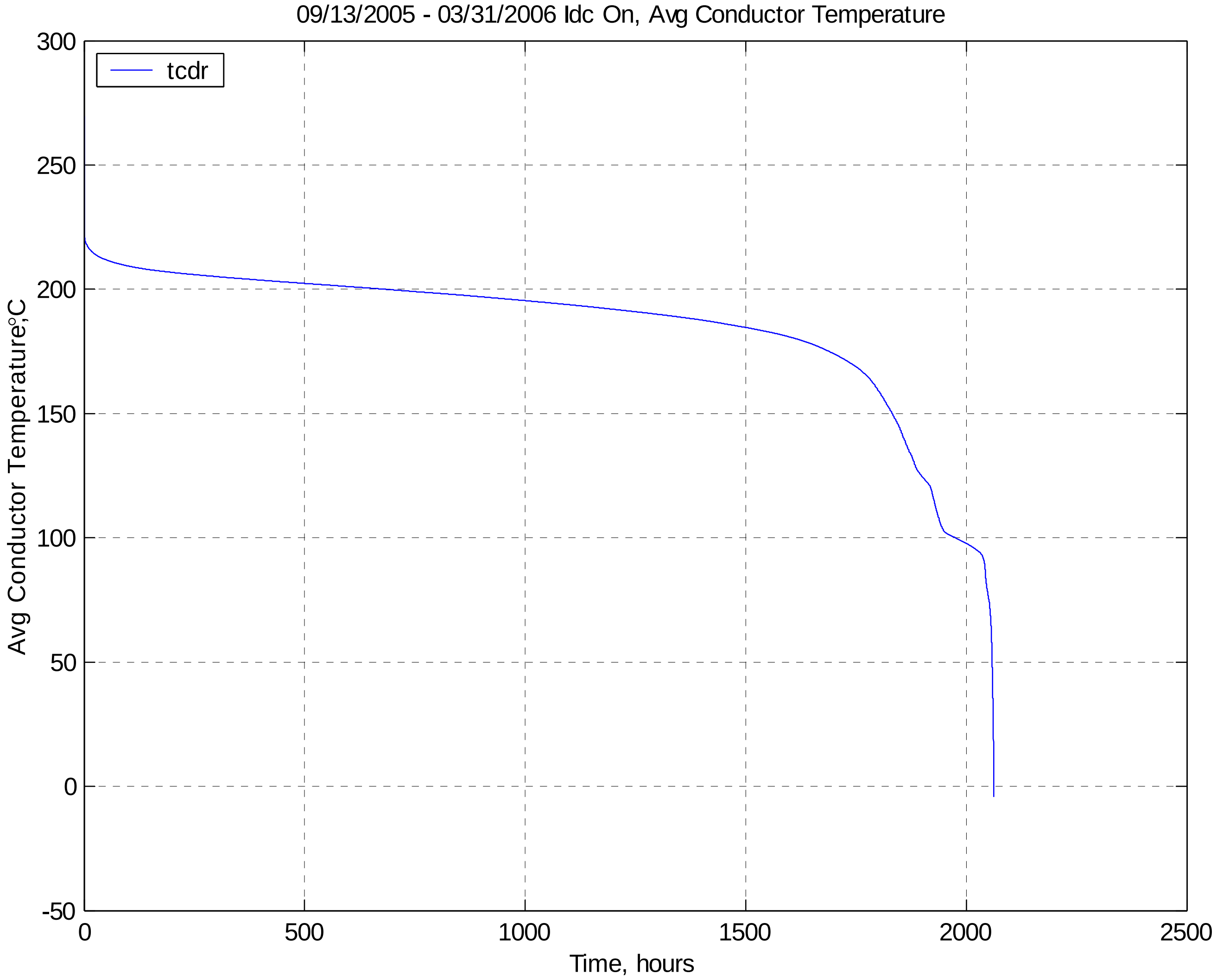
Ice on conductor, 300 lbs. for 17 hours



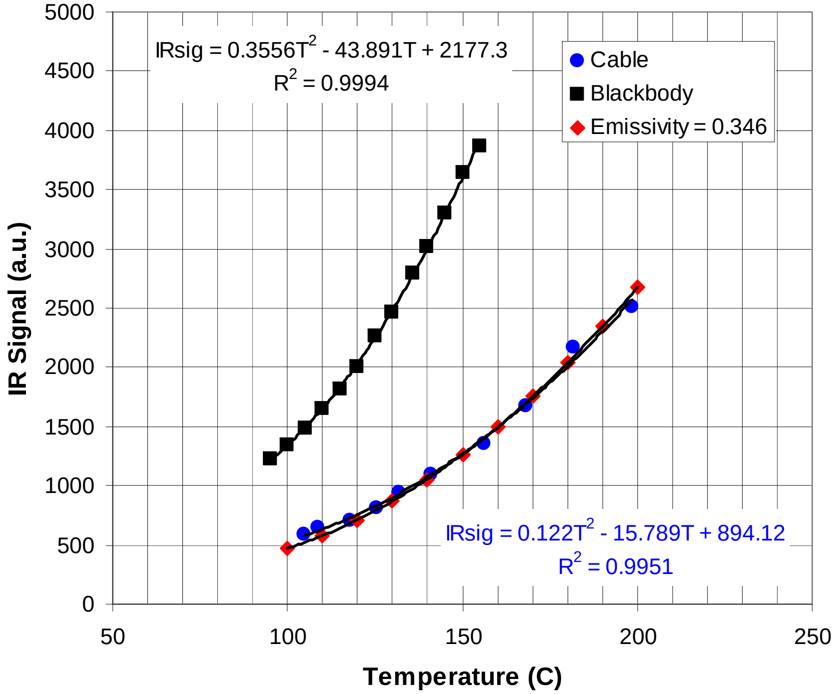
High-temperature operation – 2000 hours



Average conductor temperature during extended high-temperature operation



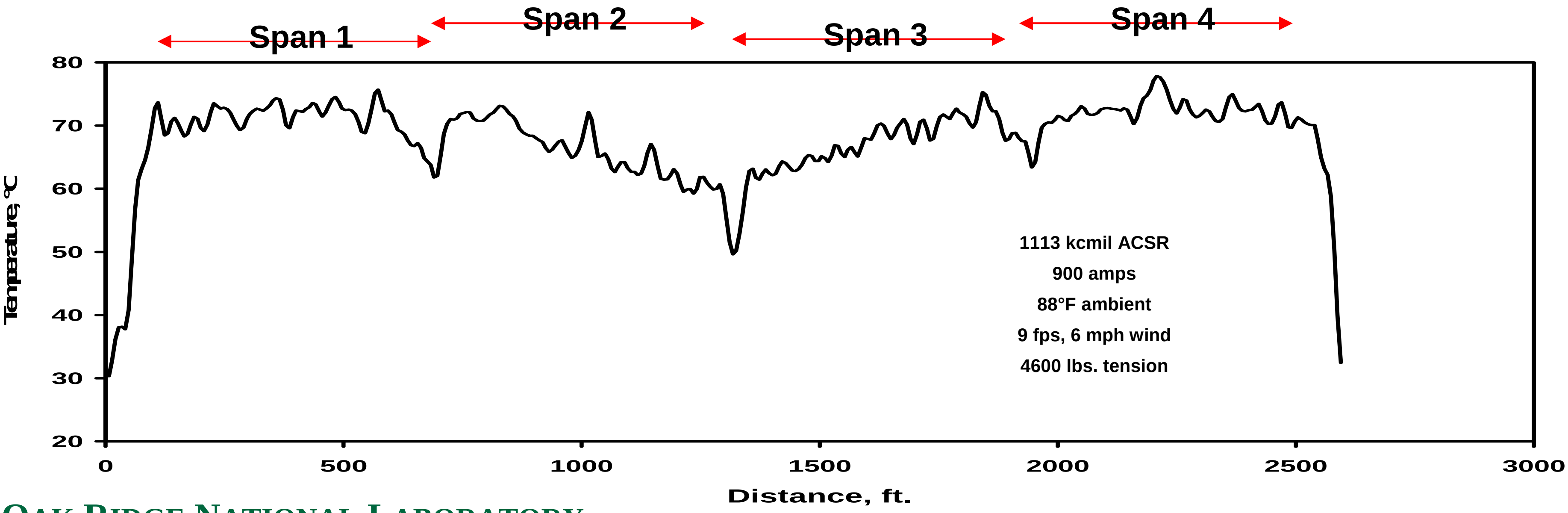
Infrared imaging is used to measure conductor emissivity, a key design parameter



Blackbody Signal is multiplied by "emissivity" until it matches conductor signal

Fiber Optic Transmission Conductor (FOTC) Measures Temperature Along Length

- **Embed optical fibers in standard bare overhead conductors**
  - Optical fiber allows temperature measurement every 2 meters along length of line
  - Temperature measurement uses the physical properties of the optical fiber (Raman backscattering)
  - Commercially available equipment used to measure temperature profile
- **Manufactured by Southwire Company, Testing and Field Demonstration**
  - Small scale verification test at ORNL in 2001
  - Field tested at ComEd, Feb. 2002 to present on 230 kV line
  - Outdoor verification test at ORNL, Apr. – Aug. 2004

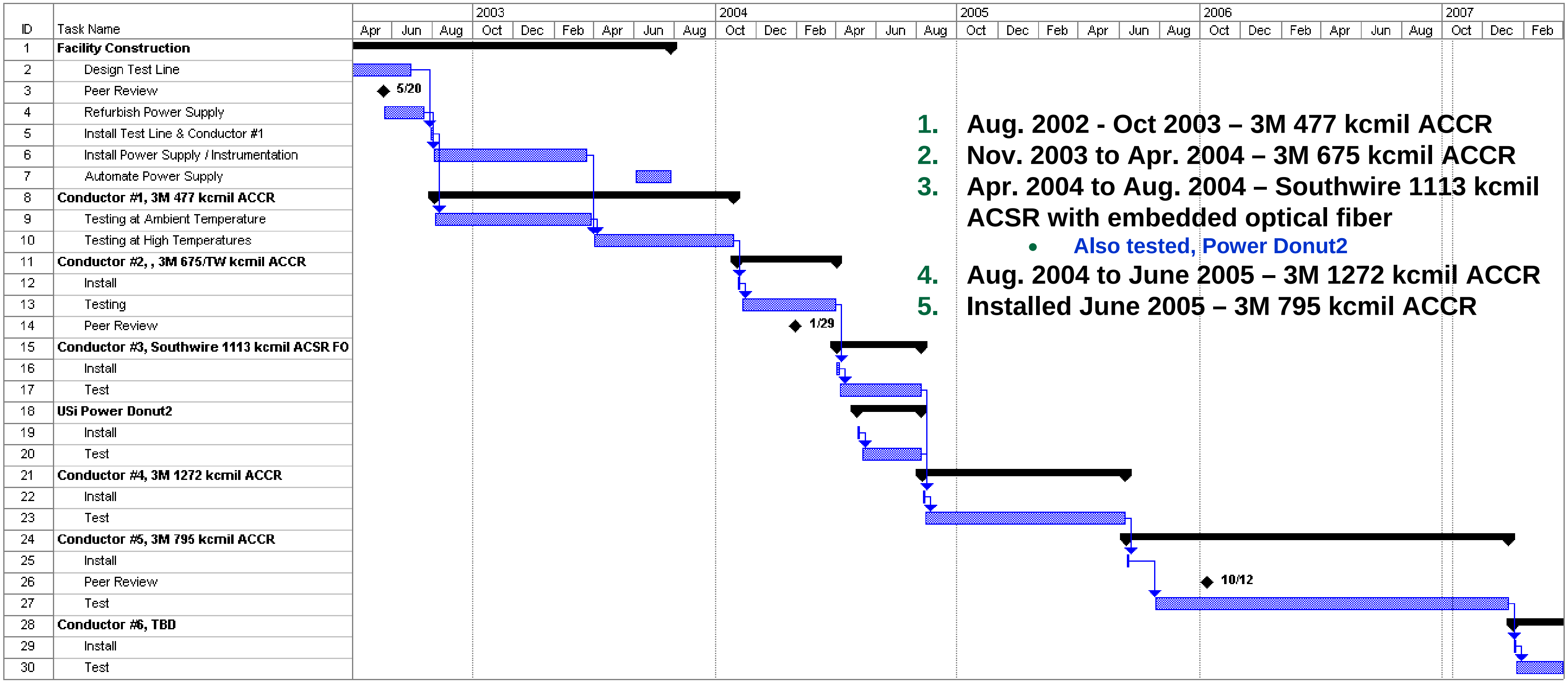


Real-Time Transmission Line Monitoring

- **Power Donut2**
  - completely self contained and self powered
  - Completely redesigned with new electronics and communications options
  - attaches to the conductor using hot stick
  - measures current, voltage, MW, MVars, MWh, conductor temperature, conductor inclination
  - stores data on board
  - transmits data continuously or on demand
- **Testing at ORNL to gather operating data on a new measurement feature**
  - Measuring conductor incline to determine conductor sag
- **Line Rating Systems**
- **Manufactured by USi, Armonk, NY**
  - www.usi-power.com

Wireless Communication to Ground Station

Project Schedule



ID	Task Name
1	**Facility Construction**
2	Design Test Line
3	Peer Review
4	Refurbish Power Supply
5	Install Test Line & Conductor #1
6	Install Power Supply / Instrumentation
7	Automate Power Supply
8	**Conductor #1, 3M 477 kcmil ACCR**
9	Testing at Ambient Temperature
10	Testing at High Temperatures
11	**Conductor #2, , 3M 675/TW kcmil ACCR**
12	Install
13	Testing
14	Peer Review
15	**Conductor #3, Southwire 1113 kcmil ACSR FO**
16	Install
17	Test
18	**USi Power Donut2**
19	Install
20	Test
21	**Conductor #4, 3M 1272 kcmil ACCR**
22	Install
23	Test
24	**Conductor #5, 3M 795 kcmil ACCR**
25	Install
26	Peer Review
27	Test
28	**Conductor #6, TBD**
29	Install
30	Test

1. **Aug. 2002 - Oct 2003 – 3M 477 kcmil ACCR**
2. **Nov. 2003 to Apr. 2004 – 3M 675 kcmil ACCR**
3. **Apr. 2004 to Aug. 2004 – Southwire 1113 kcmil ACSR with embedded optical fiber**
   - **Also tested, Power Donut2**
4. **Aug. 2004 to June 2005 – 3M 1272 kcmil ACCR**
5. **Installed June 2005 – 3M 795 kcmil ACCR**

FY 2003 **FY 2004** **FY 2005** **FY 2006** **FY 2007**

Project Summary
Transmission Test Facility

- **Fulfilling a programmatic goal defined in a recommendation of the National Transmission Grid Study**
- **Provides a unique transmission conductor testing facility to augment utility field tests and demonstrations**
- **Each conductor test undertaken in collaboration with industrial partner**

Laser at mid-span measure conductor sag

Questions?

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