Energy Research and Development Division
FINAL PROJECT REPORT

Demonstration of Advanced Conductors for Overhead Transmission Lines

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Demonstration of Advanced Conductors for Overhead Transmission Lines is the final report for the Demonstration of Advanced Conductors for Overhead Transmission Lines project contract number E21-WA-002 & 119 conducted by Electric Power Research Institute. The information from this project contributes to Energy Research and Development Division's Energy Technology Systems Integration Program.

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This is a reprint of the publically available final report from EPRI. This report describes a jointly funded collaborative research project to evaluate the operational performance of advanced High-Temperature, Low-Sag (HTLS) conductors. Twenty utilities funded this project. Among them, 15 utilities are from the United States, two from Canada, and one each from United Kingdom, Spain, and France. They are listed below.

American Electric Power (AEP)
American Transmission Company (ATC)
Arizona Public Service (APS)
California Energy Commission (CEC)
San Diego Gas & Electric (SG&E)
Southern California Edison (SCE)
Pacific Gas & Electric (PG&E)
CenterPoint Energy
Duke Energy
Exelon
Hawaii Electric
Long Island Power Authority (LIPA)
Southern Company
Tennessee Valley Authority (TVA)
Xcel Energy
British Columbia Transmission Company (BCTC), Canada
Électricité de France (EDF), France
Hydro One Networks, Canada
National Grid, UK
RED Electrica de Espana (REE), Spain

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Final Report, July 2008

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The report is a corporate document that should be cited in the literature in the following manner:

Demonstration of Advanced Conductors for Overhead Transmission Lines. EPRI, Palo Alto, CA: 2008. 1017448.

PRODUCT DESCRIPTION

This report describes a collaborative research project to evaluate the operational performance of advanced High-Temperature, Low-Sag (HTLS) conductors through approximately three years of field experience. The results of the project provide general information on installing, sagging, and clipping HTLS conductors and about their long-term behavior at different electrical current levels and in various geographical locales. Key information is provided on design, installation, operation, and maintenance of selected HTLS conductors and their hardware accessories.

Results and Findings

This report summarizes information on the mechanical and electrical characteristics of five types of HTLS conductors, including: Aluminum Conductor Steel Supported/Trapezoidal Wire (ACSS and ACSS/TW), Gap-type Aluminum Conductor Steel Reinforced [G(Z)TACSR], Aluminum Conductor Invar steel Reinforced [(Z)TACIR], Aluminum Conductor Composite Reinforced (ACCR), and Aluminum Conductor Composite Core (ACCC).

The report focuses on field trials at four utility test sites: CenterPoint Energy, HydroOne, Arizona Public Service, and San Diego Gas & Electric. It includes descriptions of data monitoring systems and instrumentation for each site. The report specifically includes information on the accessories used with HTLS conductors (splices, dead-ends, and terminations) and discusses the complex process of estimating service life of HTLS conductors based on the manufacturers' technical and laboratory test data as well as the field data obtained in this study.

Challenges and Objectives

Several manufacturers in United States and abroad have developed advanced new HTLS conductors for use in high-voltage transmission lines. These conductors are designed to overcome the traditional limiting factors in conductor performance in terms of strength loss and sag increase by being capable of continuous operation at temperatures above 100^{o}C while exhibiting low thermal elongation with temperature. The goal of this project was to provide EPRI member utilities with practical experience in handling, installing, and terminating these new types of conductor and to verify in practice the claims of manufacturers regarding their performance in an operating transmission line.

This project is intended to document specific aspects of stringing, sagging, and clipping of various commercially available HTLS conductor systems and to verify that the actual physical behavior of HTLS conductor in an operating transmission line is consistent with various manufacturer-supplied design parameters in use by utilities. The ultimate goal of this work is to help utility participants choose when to use such conductors, how to choose between various types, and how to avoid problems during installation and over the life of the line.

Applications, Values, and Use

The project offered a unique opportunity for participating utilities to gain real-world experience that will aid them in designing, specifying, handling, installing, inspecting, and maintaining advanced HTLS conductors. The field trials, laboratory tests in this project and additional future tests will make it possible to evaluate the long term-performance of the new conductors and their associated splices and dead-ends and will eventually result in guidelines in the form of a combination of written reports, videos, and classroom and field training.

The demonstration aims to raise confidence in using HTLS conductors and thus accelerate the application of the technology to increase power flow in the existing transmission circuits. The results of this project will position utilities as informed buyers and users of this technology.

EPRI Perspective

This general report is one of two final reports on EPRI's HTLS project. A second, more detailed, technically oriented report is scheduled for publication in the first half of 2009. The primary target audience for this general report includes utility executives, managers, system planners, and line design engineers who are looking for reliable information on HTLS conductors and their likely application to uprating existing lines.

Approach

HTLS conductors were installed at four utility test sites, and the project team documented installation procedures. Once the lines had been energized, the team monitored a variety of conductor parameters. They continuously recorded sag, tension, weather, and line current data and manually collected other parameters—splice resistance, conductor and hardware temperature, corona, electric and magnetic field profiles, and visual data—at regularly scheduled intervals over the test period.

Keywords

ACSR
ACSS/TW
G(Z)TACSR
ACCR
Line uprating
Overhead transmission
Sag
Annealed aluminum
ACSS
(Z)TACIR
ACCC
HTLS (High-Temperature, Low-Sag)
Zirconium aluminum
Ultra-high strength steel
Structure tension loads

EXECUTIVE SUMMARY

More than 80% of existing transmission lines use Aluminum Conductor Steel-Reinforced (ACSR) conductors, which can be operated continuously at temperatures up to 100°C. Beyond this temperature, the aluminum strand layers in these conductors begin to lose mechanical strength and the original design safety factors on tensile loading may be compromised. In addition, at conductor temperatures above the maximum selected in the original design, the electrical clearances to ground and other conductors may not be adequate due to excessive sag.

Given the difficulty in building new transmission lines, the normal increase in electrical load served with population, and the sometimes rapid shift in power flows resulting from open access rules for new generation, the power flow on certain existing lines may reach the line's thermal limit that is determined primarily by the phase conductor's maximum operating temperature.

In response to these challenges, manufacturers in United States and abroad have developed new conductors capable of continuous operation at temperatures above 100^{o}C without any reduction in tensile strength while exhibiting reduced rates of increase in sag with these high temperatures. Such conductors are referred to, in this report, as High-Temperature, Low-Sag (HTLS) conductors.

HTLS conductors are capable of continuous operation at temperatures between 150^{o}C and 250^{o}C, depending on the particular design, without losing tensile strength and with lower rates of sag change with temperature than for normal ACSR conductors. HTLS conductors can often replace conventional ACSR in an existing transmission line with little or no modification to supporting structures, thus saving both time and money and simplifying the regulatory processes.

While these conductors have passed industry standards tests for performance, utilities are wary of installing these yet unproven technologies without having first gained an insight into their performance in a real-world setting. Consequently, in 2003, the Electric Power Research Institute (EPRI) started a collaborative research project to evaluate the performance of a few of these advanced conductors. This project aims to provide participating utilities with information on the operational performance of these new conductors through approximately three years of field experience.

This general report is one of two final reports on EPRI's HTLS project. A second, more detailed, technically oriented report is scheduled for publication in the first half of 2009. The primary target audience for this general report—based on a consensus at the February 28, 2006 project meeting and subsequent telephone and email discussions—includes system planners who are looking for general information on HTLS conductors and inexperienced line engineers seeking insight into the process of reconductoring existing lines with HTLS conductors.

This project is intended to document unique aspects of stringing, sagging, and clipping of various commercially available HTLS conductor systems and to verify that the actual physical behavior of HTLS conductor in an operating transmission line is consistent with various manufacturer-supplied design parameters in use by utilities. The ultimate goal of this work is to help utility participants choose when to use such conductors, how to choose between various types, and how to avoid problems during installation and over the life of the line.

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1 INTRODUCTION

This report describes the objectives, methodology, and results of EPRI's High-Temperature, Low-Sag (HTLS) Project. The project is intended to document unique aspects of stringing, sagging, and clipping of various commercially available HTLS conductor systems and to verify that the actual physical behavior of HTLS conductor in an operating transmission line is consistent with various manufacturer-supplied design parameters in use by utilities.

This report describes general information related to the project and is designed for utility executives, managers, system planners and engineers who are seeking insight into the process of reconductoring existing transmission lines with HTLS conductors. A second, more detailed, technically oriented report is scheduled for publication in the first half of 2009.

Included in this report are ten sections, with background information on the drivers behind HTLS conductors and this project, a review of the state-of-the-art of HTLS conductors with discussions of terminations and splices, a description of opportunities for upgrade applications with HTLS conductors, a description of the four field test sites, a description of tests for predicting the service life of HTLS conductors, and a review of knowledge gained in the project.

To set the stage for the report, Section 1 leads off with a brief introduction to the HTLS project, with information on the background of the project, objectives, scope, tasks, schedule, and funders and participants.

Background

The demand for electric power is increasing at a rate of about 25% per decade, while new transmission facilities are being constructed at a rate of only 4% per decade. Deregulation of the power industry has allowed power to be dispatched from new low cost generation sources. This has altered the power flow patterns of the high-voltage transmission network. As a result, many transmission lines are overloaded, and transmission bottlenecks have been created, restricting power transfer from one location to another. Additional transmission capacities are therefore required. The most common way to raise transmission capacity is to construct new lines. However, today the regulatory process to acquire rights-of-way takes substantially longer than in the past in order to address environmental and public concerns. The new process thus further compounds the problem of imbalance between the demand and supply of transmission capacities.

One approach to addressing this dilemma involves optimizing the use of existing network assets to increase transmission capacity. If the power flow limitation is determined by a transmission line thermal rating, the rating can be increased by:

- Operating the existing conductors at a higher temperature.
- Replacing the existing conductors with a larger (lower resistance) conductor.
- Replacing the existing line conductors with an HTLS conductor of the same diameter as the original but capable of high temperature operation.

Each of these uprating alternatives presents challenges. Operation of older, existing conductors at higher temperatures requires a careful inspection to be certain that the conductor and its connectors are in good physical condition. Operation above 100^{o}C may cause unacceptable loss of ultimate tensile strength and increased sags at higher operating temperatures may not be possible due to minimum clearance requirements. Replacement with a larger conductor will impose higher mechanical loads on existing structures and may necessitate extensive upgrades or replacement of existing structures.

In response to the challenge of finding a reliable high temperature conductor for line uprating, manufacturers in the United States and abroad have developed HTLS conductors which can be installed and operated safely in existing lines. In many cases, HTLS conductors can be used to replace existing conventional aluminum or copper conductors with little or no modification to supporting structures.

EPRI HTLS Project

Power utilities are interested in installing these new conductors on their systems. However, there have been very few experiences with these conductors in North America. Their reliability is a major concern. Consequently, in 2003, the Electric Power Research Institute (EPRI) started a collaborative research project to evaluate the performance of a few of these advanced conductors that are capable of significantly increasing the current-carrying capacity of thermally constrained transmission lines. The two drivers behind the HTLS conductor project are:

1. **Meeting Capacity Needs.** Today networks are being forced to support power flows for which they were never designed. Upgrading the transfer capacity of existing lines through the application of HTLS conductors yields a large increase in thermal rating at modest cost that can be implemented quickly.

2. **Real-world Performance Testing.** In recent years, conductor manufacturers have brought to market a range of new, nontraditional conductor types. Although some of these conductors may have passed most or all accepted industry standards tests for performance, utilities are wary of installing these new technologies without having first gained an insight into their performance in a real-world setting.

2
SYSTEM IMPACT OF RECONDUCTORING WITH HTLS CONDUCTORS

Overhead lines are unique. They involve public safety directly both in terms of electrical clearances and structural adequacy. One of the fundamental limitations on power flow through overhead lines is limiting the conductor temperature to a level which neither causes a reduction in the conductor strength nor causes an increase in sag sufficient to infringe upon minimum electrical clearances to ground, buildings and other conductors. Conductor temperature can only be indirectly controlled by the power system operator by limiting line current. The link between line current and conductor temperature is influenced by weather conditions along the line.

Thermal, Voltage, and Phase Shift Limits for Overhead Lines

Determining the degree to which maximum power flow constraints can be eased by reconductoring an existing overhead transmission line with HTLS conductor, can be complex. The increase in permissible power flow over the reconductored line may be limited by other series equipment such as air disconnects, line traps, substation bus, or transformer bank capacity. Also, the power flow through critical interfaces (multiple “parallel” power circuits connecting power system regions) may not be greatly increased by reconductoring a single line since other circuits may still limit the total power flow.

For an overhead line, any increase in maximum allowable power flow resulting from reconductoring with HTLS conductor is dependent on its length as well as on the original design assumptions, the condition of its existing structures, and the type of conductors originally selected. As shown in Figure 2-1, increasing the thermal capacity of a 345 kV line which is more than 75 miles long will not allow higher power flows since the limit is due to voltage drop rather than high temperature of the conductor.

In general, it may be stated that maximum power flow on the transmission system is a function of the overall system topology (transmission lines, transformers, generation, series and shunt compensation, and load), and that many non-thermal system considerations can also limit the maximum power flow on a specific transmission circuit. Therefore, transmission circuit ratings are often developed on a system basis, rather than on an individual line basis. The overall limit may be between operating areas irrespective of ownership or individual lines, and may change during a day based on system conditions. Reconductoring an existing line to greatly increase its thermal limitation on power flow may or may not be economic and useful in terms of the system.

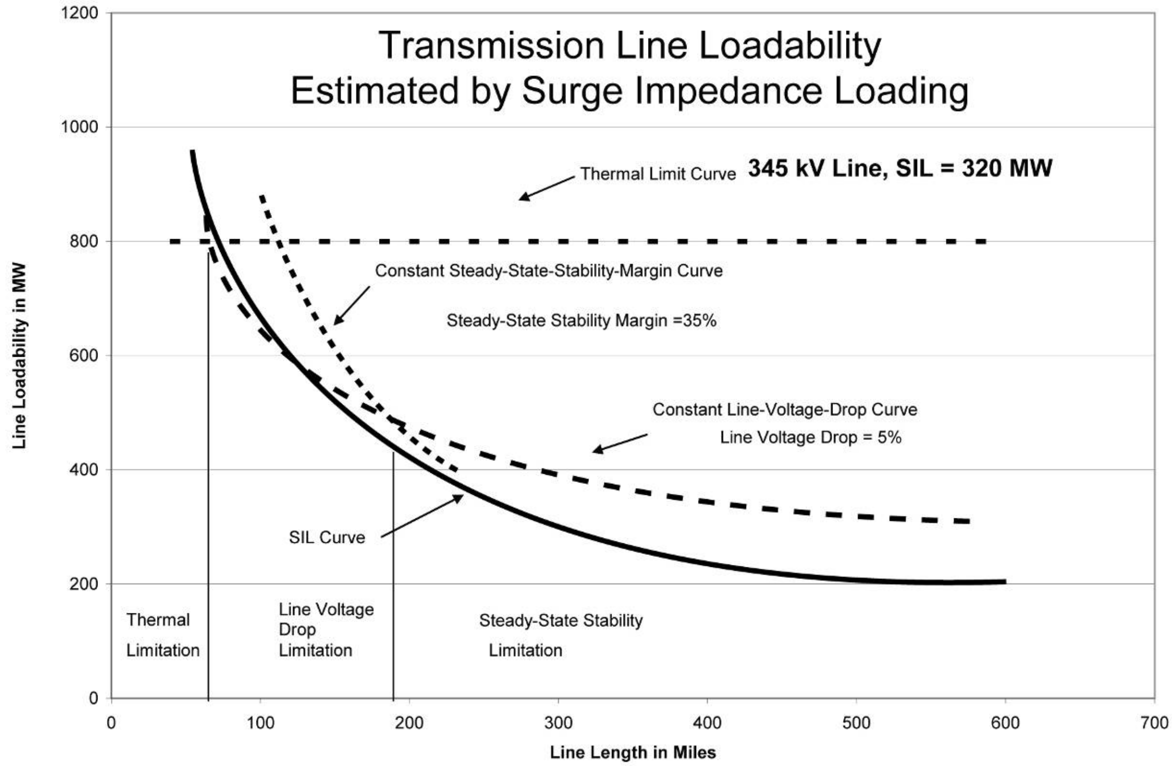


Figure 2-1
Transmission line power flow limits based on length.

Thermal Limits due to Sag

Figure 2-2 is a basic sag-clearance diagram, which illustrates how minimum ground clearance must be maintained under both heavy loading and high temperature events over the life of both new and re-rated transmission lines. The figure shows ground clearance and line sags under normal conditions, high ice/wind load, and high temperature conditions for a ruling (or "equivalent") span. Note that the sum of the minimum ground clearance, the buffer, and the sag at maximum temperature is the minimum attachment height, which determines structure height and spacing. In a detailed line design that has many different spans, this sort of sag-clearance calculation must be developed for all spans (Ehrenburg 1935, Winkleman 1959).

As can be seen from Figure 2-2, any transmission conductor must meet the minimum electrical clearance requirement, throughout the life of the line, under all environmental conditions including high wind and/or ice loading and high temperature. Therefore, sag calculations must take into account plastic elongation resulting both from high tension events - STC ("Short-Term Creep") - and long term exposure to everyday tension – LTC ("Long-Term Creep") as well as any elastic or thermal elongation that occurs. The increase in sag due to thermal elongation at high conductor temperature is based on the final sag not the initial. The elastic increase in sag due to ice or wind load is also based on final sag.

When reconductoring an existing line with HTLS conductor, sag clearance calculations must consider the initial sag of the replacement conductor, its plastic elongation over time, and it elastic and thermal elongation relative to its final sag position. HTLS conductors must do more than simply elongate less in response to high temperature, they must also be strong enough (elastic modulus) to limit elastic sag increase under ice and wind load and they must not exhibit high plastic elongation in response to high tension or long term application of more modest tension.

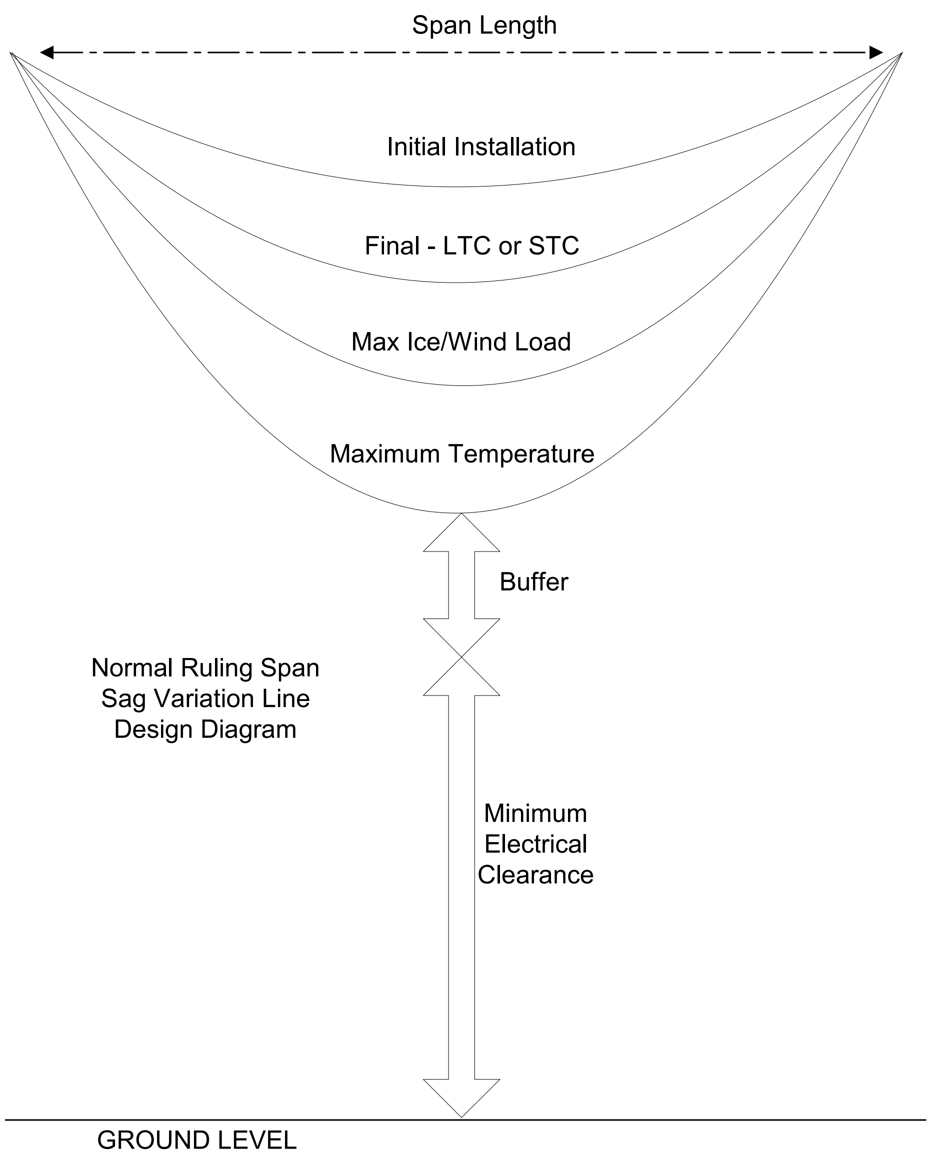


Figure 2-2
Sag-clearance diagram

Thermal Limits due to Loss of Strength

Construction codes require that maximum conductor tension not exceed a certain percentage of the energized conductor's breaking strength. A significant reduction in the breaking strength can weaken the energized conductor and lead to a tensile failure during subsequent high ice and wind loading events. To avoid this, the conductor must not operate at a high enough temperature for a long enough period of time so as to reduce its breaking strength more than 10%, and it must not be installed at such a high everyday "unloaded" tension that its strands fatigue due to wind vibration.

The American Society for Testing and Materials (ASTM) or the International Engineering Consortium (IEC - International Electrotechnical Commission) standards specify the minimum tensile strength of aluminum and copper wires, which is the stress at which the wire breaks. At temperatures above 75°C, the tensile strength decreases with time. Temperatures below 300°C do not affect the tensile strength of galvanized, aluminum-clad, or copper-clad steel wires. Thus, extended exposure of conductors made up largely of aluminum or copper wires to temperatures above 75°C can eventually reduce the line's design tension safety factor during high ice and/or wind loading events.

Figure 2-3 shows the reduction in tensile strength with time and temperature for a sample of 0.081 in. (0.2 cm) diameter hard drawn copper wire, as described in (Hickernell et al. 1949). There are 8760 hours in a year, so the diagram clearly shows that:

- sustained operation below 85ºC yields no measurable reduction of tensile strength
- sustained operation at 100ºC yields a 10% reduction in 600 hours (25 days)
- only 40 hours at 125°C reduces the wire tensile strength by 10%.

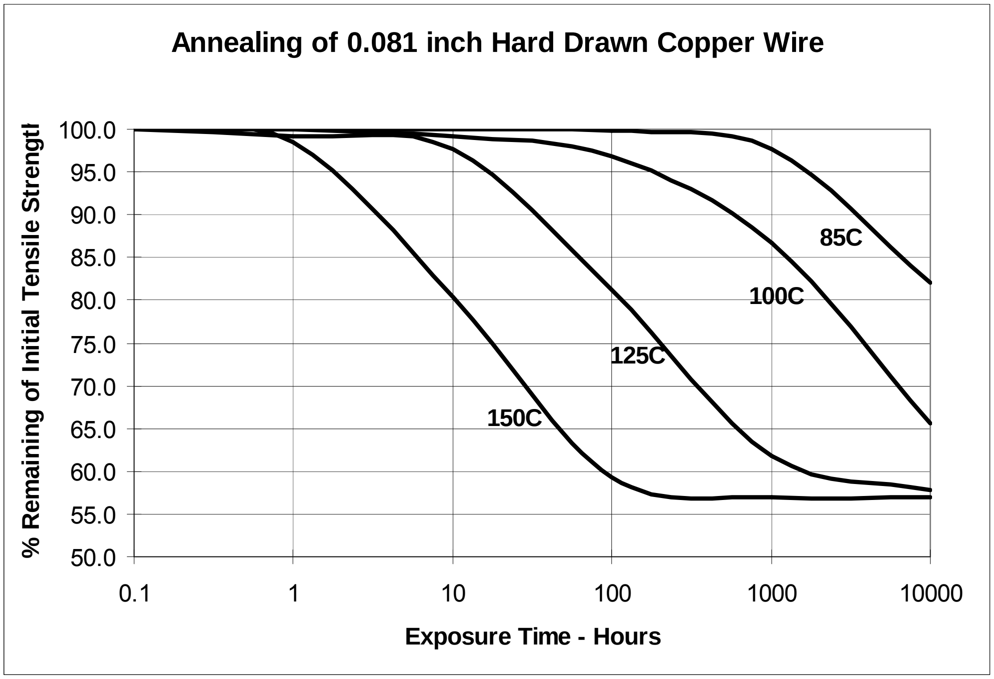


Figure 2-3
Annealing of 0.081 inch OD hard drawn copper wire at high temperature.

Figure 2-4 shows similar tensile strength reduction data for 1350-H19 “EC” hard drawn aluminum wire. (It is taken from Aluminum Association 1989). In general, tensile strength reduction of aluminum wires at temperatures of less than 90ºC is considered negligible. At 100ºC, the tensile strength of the wire is reduced by 10% after 5000 hours. At 125ºC, the tensile strength is reduced by 10% after only 250 hours.

When compared to copper, aluminum appears to anneal somewhat more slowly, though the difference is probably not important in transmission line applications. The source of the copper wire data also noted a significant amount of variation in the annealing rates for wire obtained from different manufacturers.

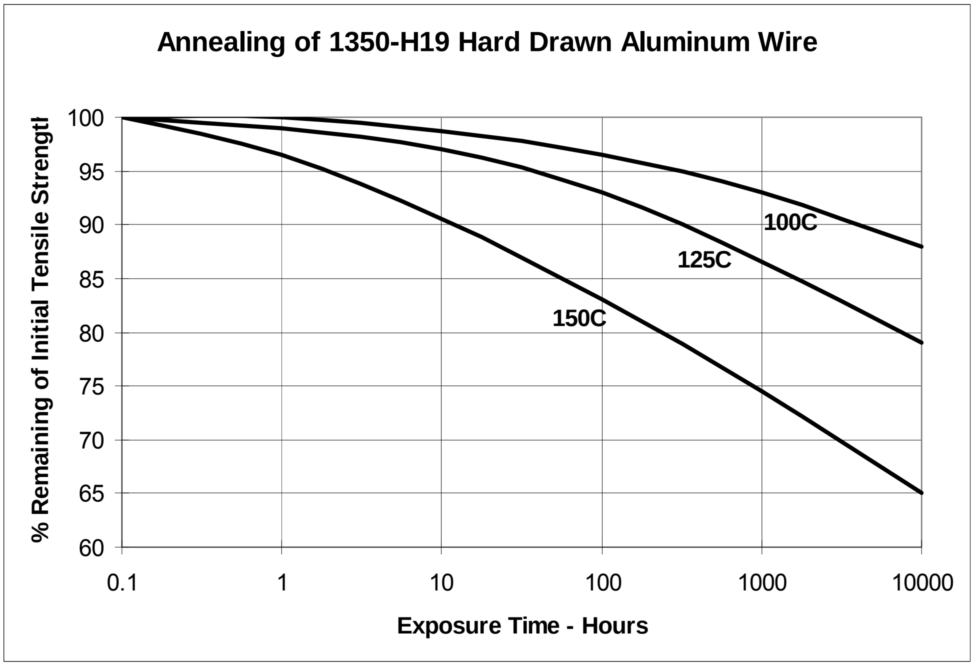


Figure 2-4
Annealing of 1350-H19 Aluminum wire at high temperature

HTLS Conductors - How They Work

As noted previously, the acronym, HTLS, stands for "High-Temperature, Low-Sag" conductors. The name summarizes the key properties of the conductors: They can be operated at high temperature (i.e. above 100ºC) for extended time periods without losing tensile strength or otherwise deteriorating mechanically, electrically, or chemically and they elongate less with temperature than normal all aluminum or steel-cored aluminum conductors.

In addition to these properties which are related to the maximum conductor temperature, HTLS conductors must also display the desirable properties associated with conventional transmission conductors:

- Mechanical properties – low weight per unit length, high elastic modulus, and low plastic elongation under high mechanical loading to so that existing lines can be reconductored with a minimum of structure modification yet remain mechanically reliable.
- Robust handling characteristics – HTLS conductors must be easily installed and terminated using methods familiar to existing experienced contractors.
- Chemical properties – Resistant to corrosion over lifetimes of 40 years or more. Insensitive to ultraviolet aging in the presence of sunlight and ozone.
- Low electrical resistance – Exhibit composite resistance less than or equal to the original conductors with the same diameter.

3
PROJECT DESCRIPTION

This research project aims to provide participating utilities with information on the operational performance of a number of new HTLS conductors through approximately three years of field experience. The project provides a unique opportunity to showcase these emerging technologies and to gain the real-world experience necessary to produce engineering guidelines that will aid utilities in designing, specifying, handling, installing, inspecting, and maintaining these conductors. In this case, the guidelines take the form of a combination of written reports, videos, and classroom and field training. Through this project, the long-term performance of such conductors, as well as associated splices and dead-ends, will be evaluated, based on field-trial and laboratory tests.

Finally, this project is envisioned as a co-operative effort between the funding utilities and manufacturers. The project does not aim to produce any intellectual property that will need to be protected by a patent. Instead the project aims to demonstrate and raise the confidence for using HTLS conductors and thus accelerate the application of the technology to increase power flow in the existing transmission circuits.

The results of this project will position utilities as "informed buyers and users" of this technology. The project also avoids duplication of research and test work completed by others in the industry. Instead, it brings these parties and their results into this project.

Scope

This project answers the following key questions:

Conductor Performance

- **Field Trials.** What characteristics of operating experience with the conductors can be gained from the field trials?
- **Laboratory Tests.** What conclusions are drawn from the experimental tests and analysis?
- **Manufacturer Claims.** How do published manufacturer claims compare to field and laboratory performance?

Design and Engineering

- **Design Parameters.** What are the design parameters (as required by line designers) for these conductors?
- **Engineering Changes.** What engineering changes (compared to standard ACSR) are necessary when designing, specifying, ordering, shipping, handling, installing, inspecting, and maintaining these conductors?
- **Existing Tower Design.** What is the impact of these new conductor types on the existing tower design? Do towers need to be redesigned to accommodate these conductors? What tower features inhibit the use of these conductors?
- **Handling**. What special handling precautions apply when shipping conductors to a site or while on site?
- **Installation.** What special tools and precautions are needed when installing these new conductors? What factors need to be considered when installing these conductors (e.g., slack-stringing versus tension-stringing)?

Conductor Aging

- **Aging Factors.** How do these conductors age, and what factors influenced aging? Further, how does aging affect performance? How does the long-term, mechanical performance of these conductors compare to the traditional conductor ACSR? If they do not compare, what are the areas of concern?
- **Long-Term Performance.** What is the long-term performance of line hardware, specifically splices and dead-ends? Performance covers repeatability of installing reliable splices and dead-ends—equipment needed to install a splice.
- **High-Temperature.** What is the effect of sustained high-temperature operation on the conductor, splice, and dead-end?
- **Connection.** How should these high-temperature conductors be connected to existing line conductors?

Conductor Fittings

- **Long-Term Performance.** How do these devices perform under high temperature over long periods of time?
- **Laboratory Performance.** Under accelerated environmental conditions, how do these products perform, and are there any concerns about the long-term integrity of these products?
- **Specifications.** What factors should be considered when specifying a conductor fitting for a particular operating environment?

Economics

- **Refurbishment Costs.** What are the comparative costs to upgrade an existing line section using different HTLS conductors?
- **New Line Costs.** What are the comparative “costs of operation” and “lifetime costs” when installing and operating networks using these new conductors as compared with the conventional ACSR?

Inspection and Condition Assessment

- **Inspection.** What techniques should be used to inspect and assess the condition of the conductors?

Engineering Guidelines and Training

- **Guidelines.** What engineering guidelines and training materials are required? What form should these materials take, and how should they be delivered?

Issues Not Addressed

This project does not address the following issues:

- **Grid.** This project does not explore the impact of these new conductors on the grid system. Upgrading the transfer capacity of a particular line within a grid system will alter power flow patterns. Changes in these patterns may potentially lead to network instability. This project focuses purely on line upgrades and performance.
- **Properties:** HTLS conductors generally operate with stable mechanical properties at higher temperatures and increase in sag with temperature at a lower rate than the original conductor. However, this issue will not be a scope of research in this project.
- **Speculative Designs.** Conductors at the research and development stage are not covered. This project evaluates only commercially or near commercially available conductors. The products considered are limited to manufacturers that are capable of manufacturing readily in amounts required in typical refurbishment projects.
- **Acceptance Tests.** This project does not aim to repeat standard conductor acceptance tests. Therefore, the project only considers conductors that have already passed most or all accepted industry standard tests.
- **New Conductors.** This project does not result in the development of new conductors.

Conductor Types

To address the issues within the project scope, conductors proposed initially for investigation were:

- ACSS or ACSS/TW (Aluminum Conductor Steel Supported)
- G(Z)TACSR (Gap–Type, Thermal Resistant Al-alloy)
- ACCR (Aluminum Conductor Composite Reinforced)
- ACCC (Aluminum Conductor, Composite Core)
- CRAC (Composite Reinforced Aluminum Conductor)

CRAC was a conductor proposed by Goldsworthy, a U.S. manufacturer, however, the manufacturer never manufactured or offered for sale. Instead, the Invar conductor was selected. In an Invar conductor, an Invar core (an alloy of nickel and steel) is used to replace the steel core of the conventional ACSR. The HTLS conductors for the project were supplied by:

- Southwire of Georgia, USA for the Aluminum Conductor, Steel Supported Trapezoidal Wire (ACSS/TW)
- 3M of Minneapolis, USA for the Aluminum Conductor, Composite Reinforced (ACCR)
- CTC of California, USA for the Aluminum Conductor Composite Core (ACCC)
- J-Power System, Japan for the Gap-Type Aluminum Conductor Steel Reinforced (GTACSR)
- LS Cable, Korea (formerly LG Cable) for the Zirconium-Type Aluminum Conductor Invar steel Reinforced (ZTACIR),

Tasks

The scope of work includes mainly six tasks. Each task is briefly described below.

Task 1 – Test Site Selection

Candidate test lines and associated test spans were evaluated. Suitable sites for the high-temperature, low-sag conductors were then selected. Four sites were chosen for the five conductors, as shown in Table 3-1.

Table 3-1
Conductor Test Sites

Host Utility	Field Trial Location	Data Collected since	Conductor Tested
CenterPoint Energy	Houston, Texas	May 26, 2003	ACSS/TW (Southwire)
Hydro One	Ottawa, Canada	October 24, 2004	Gap & Invar (J Power and LS Cable)
Arizona Public Service	Phoenix, Arizona	June 17, 2005	ACCC (CTC)
San Diego Gas & Electric	Oceanside, California	July 21, 2005	ACCR (3M)

Line designs were conducted for the conductors. This exercise generated the engineering tasks for reconductoring.

Task 2 – Reconductoring

This task includes the purchase of the conductor, temporary removal of the existing conductor, the possible modification of the towers, installation of the new conductors and associated line hardwares, and commissioning and energization of the line.

Task 3 – Field Monitoring, Laboratory Testing, and Interim Reporting

This task covers the selection and installation of field monitoring equipment, such as video sagometer, load cells, vibration recorder, and weather stations to monitor the long-term performance of the conductors and associated hardware. Conductor sag and tension were monitored continuously through sagometer and load-cells. Measurement of electric and magnetic field profiles under the transmission lines, measurements of hot spots on surfaces of conductors and hardwares (such as splices, dead-ends, and towers), measurement of splice resistance, and measurements of vibrations were taken during each site visit. These field measurements provide utilities with necessary information on the operational performance of new HTLS conductors through approximately three years of field trial experience.

Task 4 – Development of Supporting Engineering Guidelines

Under this task, EPRI develops and delivers Engineering Guidelines covering the design, specification and installation of these HTLS conductors. These guidelines will be in the form of a demonstration on installation, videos of the field installation, a workshop, and a technical report. These guidelines are directed at line designers, line inspectors, and field and maintenance crews.

Task 5 – Final Reporting

Compilation and analysis of the field data in a final project report, including recommendations and application guides. This report also contains an analysis of the cost options.

Task 6 – Test Site Decommissioning

This task assumes that the host utility wishes to remove the conductor from the test spans and restore the line to its original conductor. Restoration of original conductors is under this task. Removal of HTLS conductors is under host utility's discretion.

Schedule

Field trials of these HTLS conductors were started in the summer of 2003. Originally, it was planned that each type of conductors would be subjected to 3 years of high operating temperatures. Due to difficulties in procuring HTLS conductors and in acquiring field trial sites, the project was extended to enable the project to collect three summers of high operating temperature data. The updated schedule is as follows:

- Data Collection: Continued to May 2008
- Development of Methodology for Conductor Life Prediction: Continued to December 2008
- Evaluation of Conductor Performance by Laboratory Tests: Continued to December 2008
- Completion of Field Trial and Analysis: December 2008
- Publication of General Report entitled "Demonstration of Advanced Conductors for Overhead Transmission Lines": July 2008
- Publication of Technical Report: June 2009

Funding Members

Twenty utilities are funding this project. Among them, 15 utilities are from the United States, two from Canada, and one each from United Kingdom, Spain, and France. They are listed below.

1. American Electric Power (AEP)
2. American Transmission Company (ATC)
3. Arizona Public Service (APS)
4. California Energy Commission (CEC)
5. San Diego Gas & Electric (SG&E)
6. Southern California Edison (SCE)

7. Pacific Gas & Electric (PG&E)
8. CenterPoint Energy
9. Duke Energy
10. Exelon
11. Hawaii Electric
12. Long Island Power Authority (LIPA)
13. Southern Company
14. Tennessee Valley Authority (TVA)
15. Xcel Energy
16. British Columbia Transmission Company (BCTC), Canada
17. Électricité de France (EDF), France
18. Hydro One Networks, Canada
19. National Grid, UK
20. RED Electrica de Espana (REE), Spain

Participants

The project was managed by EPRI. Field trial sites were offered by four utilities—CenterPoint Energy, Hydro One, Arizona Public Service, and San Diego Gas & Electric—who also provided labor and material for the installation. Manufacturers were on site during conductor stringing. Monitoring equipment was installed by EPRI staff with assistance from the utilities. Regular site inspections were conducted by EPRI staff. In addition, two research organizations were involved in this project. Oak Ridge National Laboratory (ORNL) performed metallurgical and mechanical tests on ACSR and connections in an attempt to develop a methodology for predicting the service life of HTLS conductors. Due to the complexity of the subject, the focus was on the behavior of the connection. The Research and Development Division of the Électricité de France (EDF) was responsible for the assessment of service life of an epoxy-based carbon composite core.

4
HTLS CONDUCTOR MATERIALS

The vast majority (approximately 80%) of bare stranded overhead conductors used in transmission lines consist of a combination of 1350-H19 (nearly pure aluminum – 1350 - drawn to the highest temper possible – H19) wires, stranded in one or more helical layers around a core consisting of one or more galvanized steel strands. By varying the size of the steel core, the composite tensile strength and elastic modulus of an ACSR conductor of given resistance can be varied over a range of 3 to 1.

The mechanical and electrical properties of ACSR (and all aluminum conductors such as AAC, AAAC, and ACAR) are quite stable with time so long as the temperature of the aluminum strands remains less than 100^oC. Above 100^oC, the work-hardened aluminum strands lose tensile strength at an increasing rate with temperature though the steel core strands are unaffected by operation at temperatures up to at least 300^oC (though the galvanizing may be damaged by prolonged exposure to temperatures above 200^oC) .

The sag-temperature behavior of ACSR is also dependent on the size of the steel core. At moderate to low conductor temperatures, the thermal elongation rate of ACSR is between that of steel (11.5 microstrain per ^oC) and that of aluminum (23 microstrain per ^oC). For example, with Drake ACSR, the thermal elongation is 18.9 microstrain per ^oC, at a conductor temperature below the kneepoint temperature (about 70^oC under final conditions) Above the kneepoint temperature, the thermal elongation of any ACSR conductor is approximately that of steel alone (11.5 microstrain per ^oC).

HTLS conductors are able to operate continuously at temperatures above 100^oC (the HT part) and exhibit thermal elongation rates which are less than ACSR (the LS part). No HTLS conductor can be stranded out of conventional 1350-H19 aluminum wires and ordinary galvanized steel wires.

As shown in the following tables, the wire materials used for HTLS conductors are capable of continuous operation at temperatures in excess of 100^oC with stable electrical and mechanical properties. For example, annealed aluminum strands can be run continuously at 300^oC without any deterioration in conductivity. As will be discussed in later chapter, all of the HTLS conductors considered in this study consist of a high strength core surrounded by one or more layers of aluminum wires which carry most of the electrical current. For those HTLS conductors with annealed aluminum strands, the conductor stiffness and breaking strength is largely determined by the core. For those HTLS conductors with Zirconium aluminum strands, the composite conductor strength and stiffness depends on both the reinforcing core and the aluminum strand layers.

With the exception of the CTC carbon fiber composite core, the various aluminum alloys and the reinforcing materials are normally in wire form with a wire diameter of the order of 0.1 to 0.2 inches. In certain designs, the aluminum wires are provided with a trapezoidal cross-section in order to maximize the aluminum area for a given conductor diameter. The reinforcing core wires are typically round. The properties of the wires vary with wire diameter. Generally the smaller the wire, the more work hardening done in drawing it and the higher its tensile strength, though such variations with wire diameter are typically modest.

As can be seen in Table 4-1 and Table 4-2, the properties of the conducting aluminum wires and the reinforcing core wires are dramatically different. These differences can be used to advantage in various designs.

Table 4-1
Characteristics of aluminum and aluminum alloy wires

Type of Aluminium		**Minimum Conductivity [%IACS]**	**Typical Tensile Strength [Mpa] [kpsi]**	**Allowable Operating Temperature(ºC)**	
				Continuous	Emergency*
Hard Drawn 1350 aluminum	1350-H19 (HAL)	61.2	159 – 200 23 - 29	90*	125*
Thermal Resistant Zirconium aluminum	TAL	60	159 – 176 23 - 26	150	180
Extra Thermal Resistant Zirconium aluminum	ZTAL	60	159 – 176 23 - 26	210	240
Fully Annealed 1350 aluminum	1350-0	61.8**	59 – 97 8.5 – 14	350	350

* - Manufacturers often suggest performing rating calculations at 75^{o}C/100^{o}C
** - Typical conductivity for annealed aluminum is 63.0%.

Table 4-2
Characteristics of reinforcing core materials.

Core material	Min. Tensile Strength @tensile failure [kpsi]	Modulus of Elasticity [Gpa] [Mpsi]	Min. elongation at tensile failure %	Coef. Of Linear Expansion ($x10^{-6}$) per ^oC	Allowable Operating Temperature(°C)	
					Continuous	Emergency
A Galv. Steel Zn-5Al-MMSteel(B802)	200-210	206 29	3.0-4.0	11.5	180 250	200 350
A Galv. HS (B606) Zn-5Al-MM HS (B803)	220-235	206 29	3.0-3.5	11.5	180 250	200 350
A Galv. UHS Zn-5Al-MM UHS	265-285	206 29	3-3.5	11.5	180 250	200 350
CTC Carbon Fiber composite core	310-360	114 17	2.0	1.6	180	200
3M Ceramic Fiber reinforced aluminum	200	220 32	0.64	6.0	250	300
Alum. Clad (AW) 20.3% IACS	150-195	162 24	3.0	13.0	150	200
Alum. Clad Invar Steel 14% IACS	175-185	152 22	3.0	3.7	210	240

As discussed in the next section of this report, the temperature limits and typical mechanical and electrical characteristics of any composite HTLS composite conductor is a complex combination of these material properties and the connectors, terminations, and hardware provided by the manufacturer.

Comments on HTLS conductor materials

Notice some of the unique properties of the HTLS conducting component materials as described in Table 4-1. In contrast to ordinary 1350-H19 aluminum, TAL and ZTAL aluminum can be operated at 150^{o}C and 210^{o}C, without any loss of tensile strength, and annealed aluminum (1350-0) can be operated continuously at 350^{o}C without any change in mechanical or electrical properties. These aluminum wires have approximately the same electrical conductivity as 1350-H19.

5
DESCRIPTION OF HTLS CONDUCTOR SYSTEMS

Introduction

The most common conductor used in the utility transmission line applications is ACSR, consisting of one or more layers of aluminum strands wrapped helically around a core consisting of one or more galvanized steel strands. Although this very common conductor consists only of aluminum, steel and zinc, it's mechanical and electrical behavior is surprisingly complex as the electrical current through it and the conductor weight varies widely over the 40+ year life of a modern transmission line.

Terminations, splices, hardware, and installation procedures for standard ACSR overhead conductors are well understood, and problems are relatively rare when manufacturer's installation instructions are followed. The majority of line hardware associated with the suspension and support of the ACSR conductors has been designed to operate at a maximum temperature of 100°C or less. The introduction of new types of conductor may require conductor accessories to withstand temperatures as high as 250°C. The electrical connection of 250°C conductor poses not only special concerns for the tensile properties of the dead-end fittings, but also the additional problems associated with the high-temperature electrical interface. Moreover, there is a need for new equipment designs and procedures to handle the accessories. It seems likely that problems and uncertainties involving tension stringing, termination, splices, and support of new types of HTLS replacement conductors will be a primary focus in subsequent field tests.

The long-term reliability of ACSR conductor systems depends not only on the conductor itself but also on the connectors, terminations, and hardware supports that are specifically designed to work with the conductor. Many times, it has been found that the ability of the conductor system to withstand severe ice loads, high winds, or very high temperatures, is limited by the connectors and hardware rather than by the conductor itself. HTLS conductor systems are no different. There is no point in providing HTLS conductors for overhead lines unless they are supplied with connectors and hardware that is reliable and easy to install.

In the same sense as ACSR, HTLS conductors may consist of relatively simple wire materials, yet behave in ways that can be quite complex. In the last section of this report, the properties of the wire materials used in HTLS conductors are described in Table 4-1 and Table 4-2, yet the various combinations of these materials into HTLS conductors is not always easy to understand. Also, as with ACSR, the long-term reliability of the various HTLS conductor systems depends heavily on the connectors and support hardware.

This section of the report describes the electrical and mechanical properties of the various composite HTLS conductor systems made up of the materials described in Section 4.

Conventional ACSR versus HTLS Conductors

ACSR conductor (see Figure 5-1) has a steel core, consisting of one or more steel wires, surrounded by one or more layers of 1350-H19 aluminum wires. 98% to 99% of the electrical current in ACSR flows in the aluminum strands. Depending on the relative size of the steel core and the aluminum wire cross-section, as little as 15% and as much as 65% of the composite ACSR strength is due to the steel core.

1350-H19 aluminum wires, which are nearly pure aluminum, begin to anneal slowly at around 93^{o}C. At 100^{o}C, 125^{o}C, and 150^{o}C, these aluminum wires lose 10% of their ultimate tensile strength in a year, two weeks, and 12 hours, respectively. Beyond 150^{o}C, aluminum strands rapidly anneal but the steel core wires are not affected by these temperature levels.

With regard to sag at high temperature, the steel core elongates at approximately half the rate of the aluminum layers so that conductor tension is transferred from the aluminum layers to the steel core as the conductor temperature rises. At a sufficiently high temperature, all of the conductor tension is in the steel core and the elongation rate beyond this “kneepoint” temperature is essentially that of steel alone. The proportion of total tension carried by the aluminum layers and the steel core varies with the relative areas of steel and aluminum, the temperature of the conductor and the tension history (creep elongation).

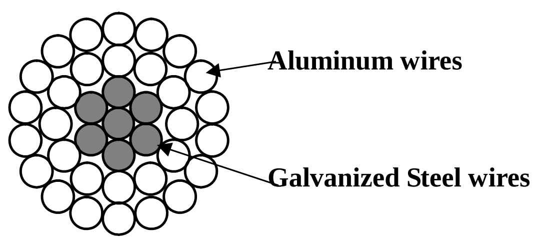


Figure 5-1
Cross-section of 30/7 ACSR conductor

General Description of HTLS Conductors

As noted previously, the acronym, HTLS, stands for “High-Temperature, Low-Sag” conductors. The name summarizes the key properties of the conductors: They can be operated at high temperature (i.e. above 100^{o}C) for extended time periods without losing tensile strength or otherwise deteriorating mechanically, electrically, or chemically and they elongate less with temperature than normal all aluminum or steel-cored aluminum conductors.

All HTLS conductors consist of a high-strength, low-elongation core surrounded by high-conductivity, aluminum strands. Each conductor has certain advantages and disadvantages, which are briefly discussed in this chapter. With the exception of ACSS, utility field experience with HTLS conductors operating at such high temperatures is very limited.

In addition to the HTLS conductor properties which are related to the maximum conductor temperature, these conductors must also display the desirable properties associated with conventional transmission conductors:

- Mechanical properties – low weight per unit length, high elastic modulus, and low plastic elongation under high mechanical loading so that existing lines can be reconductored with a minimum of structure modification yet remain mechanically reliable.
- Robust handling characteristics – HTLS conductors must be easily installed and terminated using methods familiar to existing experienced contractors.
- Chemical properties – Resistant to corrosion over lifetimes of 40 years or more. Insensitive to ultraviolet aging in the presence of sunlight and ozone.
- Low electrical resistance – Exhibit composite resistance less than or equal to the original conductors with the same diameter.

HTLS conductors considered in this study are:

- **ACSS and ACSS/TW** – Aluminum Conductor Steel Supported/Trapezoidal Wire – Annealed aluminum strands over a conventional steel stranded core. Operation to 250ºC.
- **G(Z)TACSR** – Gap-type TAl (heat resistant) Aluminum Conductor Steel Reinforced. Operation to 150ºC.
- **(Z)TACIR** – ZTAl (Extra heat resistant) Aluminum Conductor Invar steel Reinforced. Operation to 150ºC (TAl Aluminum Alloy) and 210ºC (ZTAl Aluminum Alloy).
- **ACCR** – Aluminum Conductor Composite Reinforced – High-temperature alloy aluminum (ZTAl) over a composite core made from alumina fibers embedded in a matrix of pure aluminum. Operation to 210ºC continuous and 240ºC emergency.
- **ACCC** – Aluminum Conductor Composite Core – High-temperature alloy aluminum helically wired around a hybrid polymer matrix composite core with both carbon and glass fibers. Continuous operation to 180ºC.

The operating temperature limit of a HTLS conductor is a complex combination of the properties of the outer layers of aluminum strands and the reinforcing core. Operating temperature limits for ACSR and for HTLS with high temperature zirconium alloy aluminum are normally determined by loss of tensile strength in the aluminum. HTLS conductors with annealed aluminum wires can be determined by damage to the reinforcing core. In all cases, the temperature limitation may also be determined by possible deterioration of the connectors and hardware. Therefore, operating temperature limits for HTLS conductors are normally less than or equal to the operating temperature limits of the individual component materials shown in Tables 4-1 and 4-2.

ACSS and ACSS/TW

ACSS conductor is a thoroughly tested conductor that is commercially available from multiple vendors in the United States. ACSS was first invented in the 1960s and has been sold widely in North America for over 30 years. It consists of fully annealed aluminum wires (1350-O) stranded over a core of high-strength, extra-high-strength (EHS), ultra high strength (UHS) steel, with other characteristics being similar to ACSR conductor. ACSS demands a cost premium over regular ACSR which is modest when compared to other HTLS technologies. ACSS is typically available in three different designs: standard round strand ACSS (similar to standard ACSR conductor), trapezoidal wire of equal area, and trapezoidal wire of equal diameter. In addition, it is possible to obtain all three ACSS conductor designs with any of the standard types of steel core wire having an anti-corrosion coating of hot-dipped zinc, aluminum cladding, or zinc-5% aluminum-mischmetal alloy (Zn-5Al-MM).

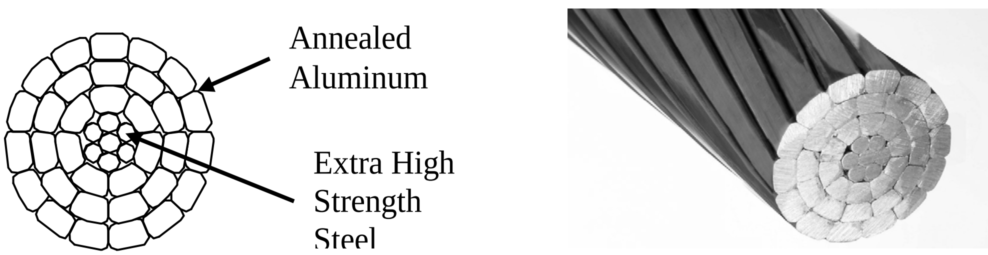


Figure 5-2
Cross-section of ACSS/TW conductor

ACSS (or ACSS/TW) has comparatively lower thermal elongation over a wide range of conductor temperatures, and the operating temperature can go as high as 300°C with Zn-5Al-MM Galfan coating on the steel core wires. The temperatures are limited to 180^{o}C when the conductor core uses ordinary hot-dipped zinc coatings. Trapezoidal shaped aluminum strands (see Figure 5-2), which minimize interstices, provide higher aluminum area compared to the equivalent diameter round-wire ACSR construction. These aluminum strands are annealed to withstand higher temperature operation; however, they are softer, resulting in more susceptibility to damage from improper handling and/or installation.

If the ACSS or ACSS/TW conductor is pre-stressed, the tension in the annealed aluminum strands is quite low and its self-damping is quite high. This allows its installation at smaller everyday sags than ACSR and helps to reduce or prevent vibration fatigue damage in challenging installations such as river crossings.

Depending upon original design conditions and conductor design, in most cases, reconductoring with ACSS/TW allows an increase of at least 30% in thermal rating of an existing line. The choice depends upon the particular uprating application. Since the conductor consists of conventional steel and aluminum, the cost premium, relative to conventional ACSR, is less than 50% in most cases. ACSS is available in the United States from three different manufacturers.

Although ACSS and/or ACSS/TW can be pulled in and sagged using the same procedures used for ACSR, particular attention needs to be given while stringing ACSS conductors. As the outer layer of the conductor is made of soft annealed aluminum strands, ACSS should not be dragged across the bare ground, over rocks, or fences etc. Parallel jaw grips should be closely sized to the conductor diameter and the clamp surface needs to be clean to minimize strand distortion.

The splicing, installation, and termination of ACSS or ACSS/TW is no more complicated than for ACSR conductors, however, the annealed strands, being very soft, should be handled with care. Also because of the annealed aluminum strands, the two-stage ACSS compression splice is somewhat longer than those designed for an ACSR conductor. ACSS conductors require two-stage sleeve splices that are a bit longer than normal ACSR splices but are otherwise conventional in application. Similarly, ACSS requires no special suspension clamp design, and tension-stringing installation is straightforward. High temperature tolerant suspension clamps must be used with ACSS or ACSS/TW in order to allow the maximum operating temperature that these HTLS conductors are capable of reaching.

G(Z)TACSR (Gap Conductor)

G(Z)TACSR, Gap-type Thermal-resistant aluminum alloy ACSR conductor, developed by J Power, Japan, is commercially available in the United States. GTACSR has a unique construction. There is a small gap between the steel core and the innermost trapezoidal-shaped aluminum layer such that the core can move independently from the aluminum layer, allowing the conductor to be tensioned on the steel core only (see Figure 5-3). The original gap-type design had only the inner aluminium layer trapezoidal, with round-wire strands used outside. The new design has all outer layers made of trapezoidal shape to maintain compact stranding and to minimize electrical resistance and increase the effective cross-sectional area on aluminum strands. The steel core is especially strengthened to increase the safety factor, because the core is responsible for withstanding the entire tensile load at high temperature. However, at low temperature the full hard aluminum strands carry load and help to limit sag under ice and wind loads. This effectively fixes the conductor's knee-point to the erection temperature, allowing the low-sag properties of the steel core to be exploited over a greater temperature range.

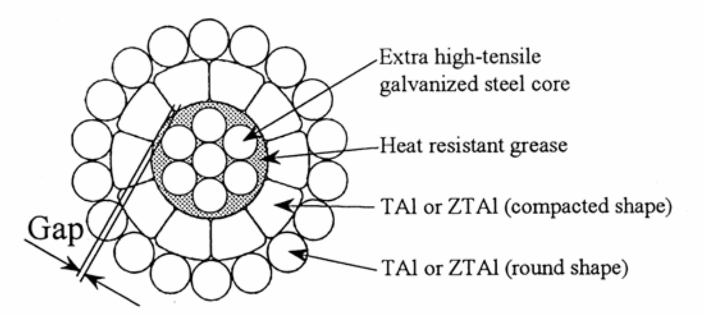


Figure 5-3
Cross-section of G(Z)TACSR Conductor

The gap is filled with heat-resistant grease (filler) to reduce friction between the steel core and the aluminum layer and to prevent water penetration. The aluminum layers being made up of either TAl (150^{o}C) or ZTAl (210^{o}C) heat-resistant zirconium alloy aluminum strands. Either type of zirconium aluminum alloy has a conductivity which is only slightly less than 1350-H19 (60% versus 61.2% IACS).

G(Z)TACSR is a Gap-type super (Z) Thermal-resistant aluminum alloy ACSR conductor built with a higher heat-resistant aluminum zirconium (Al-Zr) aluminum alloy and extra-high-strength galvanized steel core. With a small quantity of Zr added during smeltering of aluminum, there is a significant improvement in current carrying and annealing characteristics. GZTACSR can be operated continuously at 210°C without loss of tensile strength.

A special procedure is followed during the installation of G(Z)TACSR conductor. The aluminum layers of conductor must be de-stranded, exposing the steel core, which can then be gripped by a come-along clamp. The conductor is then sagged on the steel core, and after compression of a steel clamp, the aluminum layers are re-stranded and trimmed, and the aluminum body of the dead-end clamp is compressed. Although this special erection technique is different from that employed with conductors of standard construction (i.e., ACSR), the compression splices and bolted suspension clamps are similar. In addition, to ensure proper performance of this conductor, a special type of suspension clamp hardware must be installed at every three suspension spans.

National Grid, UK has successfully installed about 300 km (185 miles) length of GTACSR in its 400-kV line. More than 1500 km (930 miles) have already been installed in Libya. The Electricity Generating Authority of Thailand (EGAT) has also installed about 500 km (310 miles) of gap conductor, and it plans to add more in its 220-kV system. In addition, there are other installations (more than 300 km or 185 miles) in Saudi Arabia, Qatar, and other Asian countries. Extensive laboratory test data and detailed installation instructions are also available from the manufacturer. The installation of this conductor is more complex and labor intensive than ACSR. Its termination requires the unwinding of aluminum wires at each termination and splice. The high-temperature thermal elongation has been verified by test. Special semi-strain-type suspension fittings are required for the long lines.

The special construction of gap-type conductors and their increased capacity require that accessories and the possible combinations that involve the accessories be specially designed. Some examples of accessories that are peculiar to certain HTLS (e.g., gap type) conductors include the following photograph (Figure 5-4), which shows the termination procedure for GTACSR conductor before being installed. Here the aluminum strands are shown as the crew is separating them in order to grip the steel core. Since the conductor core is responsible for carrying 100% of the tensile load of the conductor, compression-type dead-end clamps used in gap-type conductor require a relatively larger size than those used for ACSR with the equivalent diameter to allow for the increased current capacity.

Figure 5-4
Removal of gap conductor strands at the termination at the EPRI Lenox Lab

Gap conductors have grease in the gap between the core and the aluminum strands. This grease needs to be replaced with high-temperature grease before the steel-end is crimped to grip the core at 50% overlap (see Figure 5-5).

Unlike ACSR conductors, gap-type conductors require that the conductors must be installed such that the aluminum layers are compressed while only the steel core is under tension in order to gain maximum benefit from the small-sag properties. Similarly, as the wire stranding construction of gap-type conductor is different from that of ACSR, and the current capacity is large, unique designs for termination hardware are also required for gap-type conductor.

Figure 5-5
Application of high-temperature grease on core-grip portion

ZTACIR (INVAR)

ZTACIR is a Zirconium alloy Aluminum Conductor Invar steel Reinforced conductor. The conductor is similar to ACSR conductor (see Figure 5-6); the major difference being that the core is made of high strength invar alloy wire, instead of conventional steel wire. Invar is an alloy of steel (64%) and nickel (36%). Nickel possesses a very small linear coefficient of thermal expansion which is practically invariable with heat. This property provides excellent sag control performance at high temperature beyond the knee point. Hence it is recommended to operate beyond the knee point. This conductor has relatively low sag at higher temperature. ZTACIR has a maximum continuous operating temperature of 210°C and can carry twice the current capacity of ACSR conductor. The coefficient of linear expansion of invar wire (2.8 to 3.6 x 10^{-6}) is on the order of one-third of that of galvanized steel wire. However, tensile strength of invar wire (1080 MPa) is lower than galvanized steel wire. Tensile strength of the conductor is about 8% lower than normal ACSR conductor. As the conductor has the same structure and size as of ACSR, the stringing method is also identical to that of ACSR.

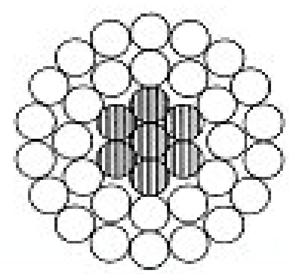


Figure 5-6
Cross-section of ZTACIR Conductor

ACCR and ACCR/TW

ACCR is built with outer layers of heat-resistant aluminum-zirconium (Al-Zr) wires (round or trapezoidal) and a proprietary fiber-reinforced aluminum matrix composite core. Both the composite core and the outer Al-Zr strands contribute to the overall conductor strength and conductivity. The outer alloy aluminum wires are round and of the same construction type as ACSR conductors. The Al-Zr layers and the core wires are helically stranded as in ACSR conductors. The composite core has a lower thermal elongation property and equal or greater strength than galvanized steel. The core wire looks physically similar to steel core, but it is eight times stronger than aluminum and about the same stiffness as the steel core. Each core wire contains thousands of small-diameter, ultra-high-strength, and aluminum oxide fibers. The ceramic fibers are continuously oriented in the direction of the wire, and fully embedded within high-purity aluminum. Currently, 3M is the only manufacturer of this type of conductor, and the production unit is based in Wisconsin, USA.

Figure 5-7
Cross-section of ACCR Conductor

The strength of this core is comparable to steel, but it possesses additional properties. For example, the alumina fibers have a lower thermal expansion than aluminum or steel; the core has a greater resistance to corrosion; it exhibits lesser creep; it has no undesirable magnetic properties. It can operate continuously at 210ºC. The outer wires surrounding the composite core are made up of high temperature-resistant ZTAL strands. ZTAL aluminum limits the maximum operating temperature of the ACCR conductor.

Xcel Energy successfully completed a field test of ACCR conductor in its 115 KV system in Minneapolis with a single 800-ft span to replace equivalent ACSR conductor in Minneapolis in 2001. More than ten utilities have now successfully installed ACCR conductor in their systems including Hawaiian Electric, Arizona Public Service (APS), Bonneville Power Administration (BPA), Western Area Power Administration (WAPA), and Pacific Gas and Electric (PG&E). Field test results appear to be positive with no unusual problems during installation or afterward. The installation of this conductor appears to be reasonably straightforward but may require special large blocks and careful handling. 3M has conducted various mechanical and electrical tests that meet the criteria for the conductors' mechanical and electrical integrity with its hardware.

Under a Department of Energy (DOE) project, a two-span ACCR line was tested in Oak Ridge National Laboratory (ORNL) at high temperature for an extended time period. ORNL published multiple field trial reports on "477, 795 kcmil, 675 TW, and 1272 kcmil ACCR conductor". 3M has invested considerable engineering effort in studying the details of the conductor's and the accessories' behavior under the realistic high-temperature conditions of this study. 3M has also developed technical information on ACCR conductor and its accessories including installation guidelines and laboratory test results. 3M also provides technical support to the potential users of ACCR conductors. ACCR conductor has been field-tested for more than five years.

The compression-type hardware for the dead-end assembly of ACCR conductors uses a modified two-part approach, as in the ACSR or ACSS conductor. One part grips the core, and then an outer sleeve grips the aluminum strands, as shown in Figure 5-8. This approach prevents notching of the core wires. The gripping method ensures that the core remains straight to evenly load the wires, and also ensures that the outer aluminum strands suffer no lag in loading relative to the core.

Figure 5-8
Termination of ACCR HTLS conductors

ACCC and ACCC/TW Conductor

Aluminum Conductor Composite Core (ACCC) cable was developed to improve several key performance metrics over conventional ACSR conductors. A lightweight circular-shaped advanced composite core – designed as a single piece rod – acts as a mechanical support and high–performance, trapezoidal-shaped, fully annealed 1350-0 aluminum strands fit well around the circular surface of the core in a helical shape with minimum interstices compared to the conventional ACSR conductor (see Figure 5-9). This leads to increase the effective cross-sectional area for aluminum strands, increasing the current carrying capacity. The cross-sectional area of the aluminum Suwannee (ACCC/TW) conductor is 30% higher than the equivalent diameter ACSR (Drake).

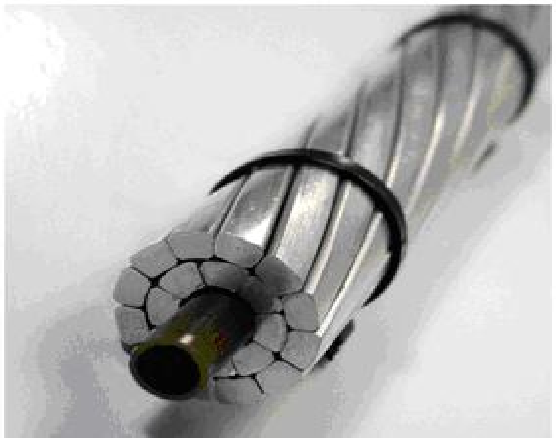


Figure 5-9
Cross-section of an ACCC Conductor

To increase the strength of the conductor, a carbon/glass fiber, polymer matrix composite core is used to replace the stranded steel core used in ACSR conductor. Carbon fibers are situated in the core, and are surrounded by a "shell" of E-glass fibers, as shown in Figure 5-10. The composite core in the ACCC is a low-density material with much lower coefficient of thermal expansion (CTE) and a high strength-to-weight ratio. The density of the composite is 1.935 mg/m^3, while the density of steel is 7.78 mg/m^3. The annealed aluminum strands allow operating continuously at elevated temperatures of up to 200°C with dramatically less sag.

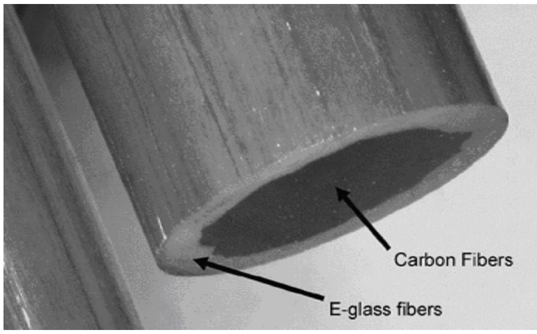


Figure 5-10
ACCC core showing the glass and carbon fiber

The composite core used in the ACCC conductor is a solid, single-piece rod with no interstices, unlike cores in ACSR and ACSS conductors. As the core has a smooth surface and it bears the overall tensile strength of the conductor, the dead-end assembly (Figure 5-11) has been designed to create a stronger crimp compared to that of ACSR conductor that forms a very solid aluminum press that fits around the composite core, as shown in Figure 5-11.

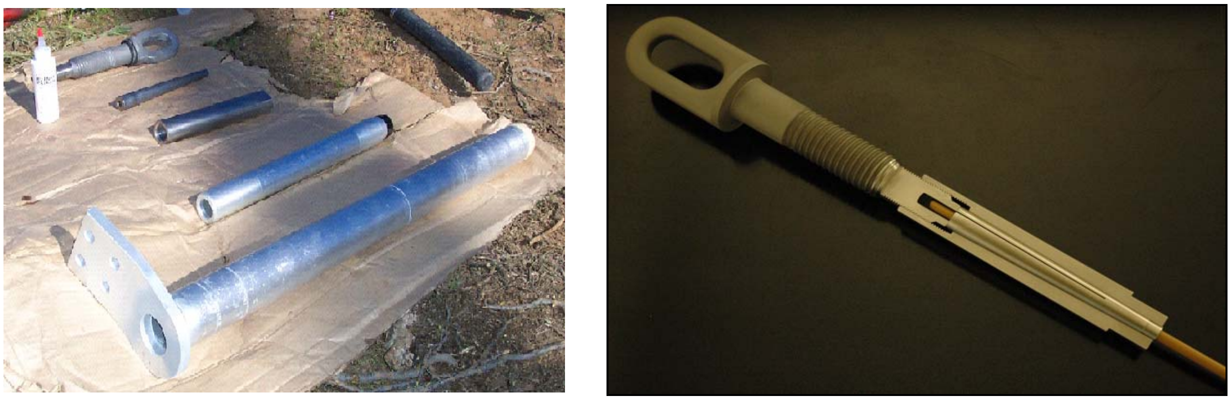


Figure 5-11
Dead-end fittings hardware used for ACCC conductor

Technology Maturity and Cost Comparison of HTLS Conductors

Field testing of HTLS conductors should include verification that recommended methods of termination, support, and tension stringing work reasonably well with ordinary utility crews. No such field tests are possible until the HTLS conductor manufacturers provide installation recommendations and confirmation that connectors, support clamps, and terminations work well at the extreme temperatures that are likely to be encountered in HTLS conductor applications.

In addition to the hardware accessories, special attention needs to be given in selecting an appropriate inhibitor for HTLS compression joints. The maximum temperature limit of 250°C for which some manufacturers are rating their HTLS conductor will cause connectors to experience internal temperatures in excess of what traditional mineral-oil-based inhibitor compounds will tolerate. The base mineral oil of such inhibitors begins to break down at 162°C. A synthetic base inhibitor has been developed that will perform in the temperature range for HTLS conductors.

HTLS conductors are more expensive than conventional conductors from the initial investment perspective. But HTLS conductors can carry significantly higher current compared to the conventional conductors (see Table 5-1). In this case, the cost associated with conventional conductors can be comparable or sometimes higher when we take into account the upgrade cost for transmission towers and accessories including land and environment for the equivalent current that HTLS conductors can carry. Table 5-1 shows the cost of various HTLS conductors with similar cross-sectional area. The cost includes the cost of the conductor only. Other technical characteristics of the conductor, such as the sag and tension behavior that determine whether structure modifications are required, must be considered to determine the overall cost of replacement. The conductor length for the US system covers ACSR conductor above 230 kV.

Table 5-1
Price Comparison for HTLS Conductors with Respect to Current–Carrying Capacity (as of March 2008)

Conductor	Current Capacity	Price	Conductor Length (miles)
Conventional ACSR	1	1	> 500,000 in US (230 kV and above)
ACSS (Round and Trap Wire, all strengths)	1.8 to 2.0	1.2 (HS steel core) 1.5 (HS285 UHS core)	34,000 in US 800 with HS285
GTACSR (Gap)	1.6-2.0	2	6,400
ACIR (Invar core)	1.5-2.0	3 – 5	12,000 (4,000 ZTACIR)
ACCR (Aluminum composite core)	2-3	5 – 6.5	500
ACCC (Carbon Fiber composite core)	2	2.5 – 3.0	1,200

The price figures are obtained from the respective manufacturers. This economic comparison does not take into account the economic benefits associated with greater revenue generated as a result of increased current throughput capacity from HTLS conductors.

Some of the HTLS conductors considered for this field test have been in the electricity market for just a few years. ACSS has been commercially available in North America since 1970. Among the newer HTLS conductors, none has seen extensive use in North America. There are a total of 20 to 40 field installations of the newer HTLS conductors throughout the United States. Many of them are only a few spans long.

The market penetration for gap and invar conductors throughout the North America is especially low. In Japan, the use of TACSR (ACSR with TAl aluminum) is used widely whereas the other Japanese HTLS conductors have seen very limited application.

Table 5-2 presents the technology status, availability of proof-of-concept tests, detailed fittings and test data, and manufacturing specifications for associated hardware and accessories.

Table 5-2
Summary of HTLS Development Status

HTLS Conductor	Proof-of-Concept Tests	Detailed Test and Fitting Data	Field Tests	Manufacturing Specification
ACSS	Yes	Yes	Yes	ASTM
ACSS/TW	Yes	Yes	Yes	ASTM
GTACSR	Yes	Yes	[3]	[2]
TACIR	Yes	Yes	[1]	[2]
ACCR (3M)	Yes	Yes	Yes	Yes*
ACCC (CTC)	Yes	Yes	Yes	Yes

[1] – No field test in the United States.

[2] – Japanese manufacturing standards exist.

[3] – Field test at National Grid.

* – Partial ASTM standards and manufacturer specifications

6
UPRATING APPLICATIONS FOR HTLS CONDUCTORS

The power transmission system, in any region, is a complex combination of lines (including underground cable) and substations. With the exception of relatively short "radial" lines connecting generating stations to the system, power flow reaching any load point in the system flows over multiple "parallel" paths (circuits). In any path (circuit), the power flow moves through multiple series elements.

Power circuits consist of series and parallel combinations of electrical equipment (each subjected to mechanical, electrical, and thermal stresses) whose collective purpose is to transmit power safely and reliably under widely varying operational situations. Each element of such circuits is typically specified to have certain power flow limits that allow their safe, reliable operation for an extended period of time (e.g., 40 years).

Increased power flow inevitably means increased electrical current flow or increased circuit voltage, since power is the product of these quantities. In general, for substation equipment and underground cables, increasing the operating voltage is difficult or impossible, whereas increasing the maximum electrical current is both possible and economic. Overhead lines are often capable of sustaining either higher voltage or higher current levels if certain modifications are undertaken.

Power transmission circuits are typically bimodal in terms of power flow. Under normal operation, it is not unusual for power transformers and lines to operate at much less than half of their power flow capacity, only approaching their operational limits under relatively rare emergency events.

There are basically three methods of increasing power flow: load control; improved modeling and monitoring; and physical modification of existing equipment. Load control devices are not considered in this report. Improved models may allow operation of equipment with reduced safety factors but without any practical reduction in safety or reliability (e.g., an improved model for the high-temperature sag of ACSR conductor). Improved monitoring of environmental factors (air temperature, wind speed, humidity, etc.) may allow the use of less conservative assumptions, again without reducing safety and reliability.

With monitors communicating data in real-time, it may be possible to run equipment at higher power levels most of the time by avoiding the use of "worst case" assumptions. This approach is called dynamic thermal ratings. It is unlikely that such real-time monitoring would allow any increase in non-thermal operating limits.

Many opportunities exist for the physical modification of overhead lines. Lines are the primary means of power transfer over long distances. They have thermal ratings just as power transformers, substation terminal equipment, and underground cables, but, for long lines, power flow limits may also be necessary to avoid excessive voltage drop or system stability problems. In addition, since the public has access to the area under lines, there may also be limits on voltage and current related to environmental effects and public safety.

Sometimes a power transmission line possesses a definite power flow limit based on its design parameters. In other situations, the power flow on a line may need to be limited because of concerns regarding voltage drop, possibility of voltage collapse, and system stability, both steady state and transient, which have little to do with the line design.

Series reactance, shunt admittance, and their combination, surge impedance, are relevant to system transfer limits. System planners have long recognized this relationship, particularly where there are prospects of changing the line surge impedance, either by adding equipment (e.g., series capacitors) or by modifying the line itself (e.g., reconductoring, voltage uprating, etc.).

Reconductoring lines with HTLS conductors can be a very cost-effective way to increase the thermal rating of an overhead transmission line, but there are a number of things that it can't do. Reconductoring an overhead line with HTLS conductors has no impact on voltage drop or on electrical phase shift along the line. Therefore, if power flow on an overhead line circuit is limited in order to keep the receiving end voltage above 95% of the sending end voltage, then reconductoring the line with a HTLS conductor will not help.

Also, if the flow of power through a particular overhead line circuit is limited in order to avoid overheating a power transformer or an underground cable in series with the overhead line, reconductoring with HTLS conductor will do nothing to change the limitation.

Similarly, HTLS conductors will do nothing to change the electric and magnetic fields produced by the line. These fields are dependent upon the physical spacing of the conductors, the diameter of the conductors, and their geometric arrangement (e.g., delta, horizontal, etc.). Replacing existing power conductors while preserving the original structures, typically leaves electric and magnetic fields unchanged.

Finally, HTLS conductor can only be used to uprate lines whose structures are in good or excellent condition. If the existing structures are in poor condition, then uprating the line with any replacement conductor, including HTLS, is simply not sensible.

Electrical Losses for HTLS Conductors

The cumulative cost of electrical losses in an overhead transmission line is a function of the phase conductor resistance, the square of the line current, and the duration of high current loading. HTLS conductors have roughly the same electrical resistance as conventional conductors having the same cross-sectional area of aluminum. They can, of course, be applied safely in lines with much higher losses (higher current) than conventional conductors.

Therefore, the cost of electrical losses is one of the issues to be evaluated in uprating existing lines.

If the line operates routinely at line currents that approach its thermal limit, then the cost of the resulting electrical losses is likely to be significant. For short lines, which experience occasional high electrical loads, HTLS conductors are often an excellent method of uprating. For longer lines, which routinely experience high loads, the addition of another line or the rebuilding of the existing line to support a larger ACSR conductor may be justified by the cost of electrical losses.

For reconductoring short lines (e.g., less than 20 miles long), electrical losses are unlikely to be significant, and the use of HTLS conductors is usually a reasonable and economic option. For longer lines, reconductoring with HTLS conductor may also be economic, if the frequency and duration of high current loads is low.

Impact of HTLS on Electric and Magnetic Fields

In the normal application of HTLS conductors, they are used to replace the original conductors of existing lines while re-using the original structures ("reconductoring"). Reconductoring normally leaves the original ground level electric field, electric induction, corona discharge levels, and audible noise levels unchanged. However, the ground level magnetic field and magnetic induction levels will increase if the line current increases as a result of the higher line thermal rating.

The levels of magnetic field associated with any transmission line are primarily a function of the conductor spacing, the geometric arrangement of the three phase conductors, and the power flow on the line. The presence or absence of a steel core within the transmission line conductors does not alter the magnetic fields outside of the conductor.

Identifying Appropriate HTLS Line Uprating Applications

The methods used to increase the thermal rating of an existing overhead line vary widely. Reconductoring an existing line with HTLS conductor is just one of many alternatives. Since HTLS conductors may be more expensive than conventional aluminum stranded conductors, they are not suitable in every uprating situation. In very general terms, the most promising applications for reconductoring with HTLS conductor involve the following scenarios:

- If the existing line's conductors are in poor condition, but the structures and foundations are in relatively good shape, then HTLS conductors are likely to be competitive with conventional conductors.
- If the structures and foundations are in good condition, the existing line's conductors are all aluminum (i.e., no steel core), and present line rating must be increased by more than 30%, then HTLS conductors are likely to be a good choice.
- If the existing line structures and foundations are in good condition, and the electrical clearances along the line are at or near to the minimums prescribed by the NESC, then reconductoring with HTLS conductor may be warranted.

- If the existing line is in good physical condition, is presently rated at a conductor temperature between 75°C and 125°C, and the minimum increase in thermal rating is in excess of 20%, then reconductoring the line with HTLS conductor is likely to prove economic.

Again, in very general terms, the least promising scenarios wherein reconductoring with HTLS conductor will prove economic or practical are the following:

- If the structures or foundations of the existing line are in poor condition, then there is little or no reason to reconductor with HTLS or conventional conductor.
- If the existing line is in good physical condition, and the rating is to be increased by less than 20%, it is likely that an alternative method of uprating will be more attractive than reconductoring with HTLS.
- If the line is more than 10 miles long, and the daily normal load peak reaches a power flow level near to the line's thermal rating, then the cost of electrical losses may indicate the need for reduced resistance rather than increased operating temperature.
- If the line is 500 kV or above, reconductoring with HTLS conductors is not typically required, because the existing thermal rating is already much higher than the limits on power flow related to voltage drop and phase shift.

As an example, consider the plot of ampacity versus maximum allowable conductor temperature, shown in Figure 6-1. Of course the relationship between ampacity and temperature limit applies to any line with this size conductor. It works equally well for the existing line or for the reconductored line with a 795 kcmil conductor.

Three temperature ranges are indicated in Figure 6-1. Range **A** goes from 49°C to 75°C. Range **B** goes from 75°C to 125°C, and Range **C** goes from 125°C to 180°C:

- The conductor temperatures in Range A are typical of unmodified existing lines built prior to 1970 according to the older NESC code, which required electrical clearances be met at 120°F rather than the "maximum conductor temperature for which the line is designed to operate" (NESC Rule 232A, 2003).
- The conductor temperatures in Range B are typical of either more recently built lines or lines that have previously undergone a thermal uprating without replacing the original conductors.
- Lines having maximum conductor temperatures in Range C are less common. Here the asset owner has typically made a special provision to handle these high temperatures safely. Special connectors, frequent inspections, and severely limited emergency durations may be required to operate ACSR in this range.

If the structures and foundations of an existing line are in good condition, and if the required increase in thermal rating is greater than 30%, then existing lines with temperature limits in Range B are prime candidates for reconductoring with HTLS conductor.

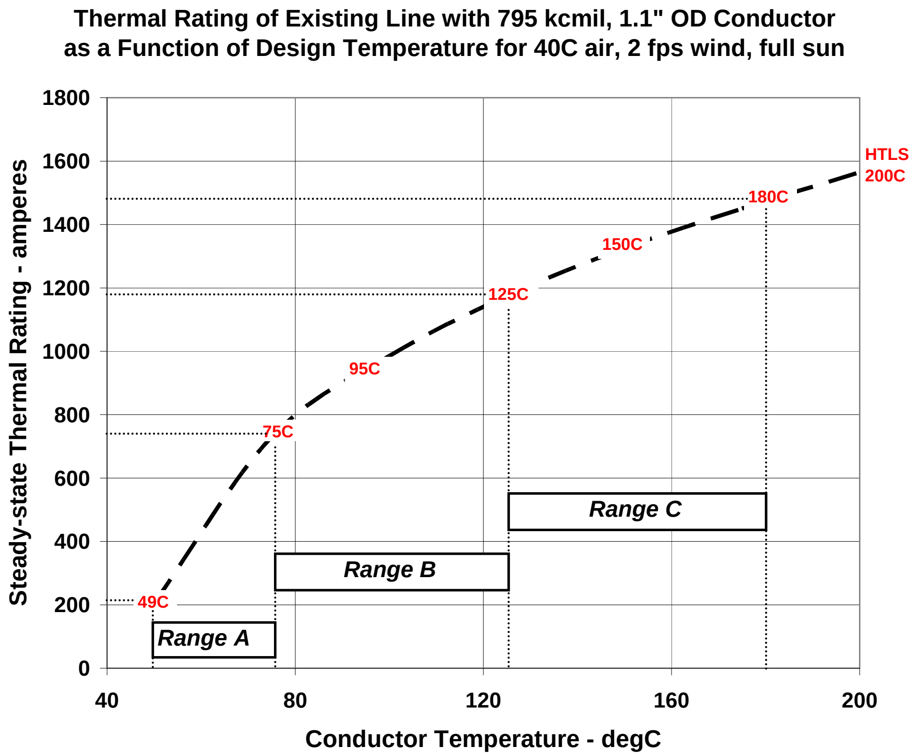


Figure 6-1
Plot of Ampacity versus Maximum Allowable Conductor Temperature

If the maximum allowable temperature of the existing line is in Range A, and the line (including conductors) is in good physical condition, then the line can typically be uprated sufficiently without needing to resort to reconductoring with HTLS conductor.

Finally, if the existing line's conductors are limited to temperatures in the temperature Range C, it is unlikely that reconductoring with HTLS will yield a large enough increase in rating to justify the cost.

In any of these temperature ranges, reconductoring with HTLS conductor may turn out to be both effective and economic, nonetheless, the most likely application of HTLS is in reconductoring existing lines with maximum conductor temperatures in temperature Range B.

Choosing the Best HTLS Conductor System in a Given Application

The field test incorporates tests and analyses of a wide range of HTLS conductors as described in the following section. In those line uprating situations, where HTLS conductor seems to be a sensible solution, there is still the matter of deciding which HTLS conductor is the best choice.

One of the primary determinants is cost. While this is a changing factor, with the exception of ACSS, the other types of HTLS conductor cost from 2 to 6.5 times as much as conventional conductor of the same size. ACSS typically costs less than 50% more than conventional conductor. This is one of the major reasons that ACSS is so widely used in North America.

<u>Maximum operating temperature</u> is similar for most of the HTLS conductors studied. The range of manufacturer's recommended maximum operating temperature for ZTAl or annealed aluminum is from 200°C to 250°C. In almost any practical application, the difference in rating between a conductor at 200°C and one at 250°C is a secondary consideration.

<u>Rate of sag increase with temperature</u> varies over a fair range between the HTLS designs. In an application where electrical clearances are very close to NESC Code minimums, conductors like ACCR and ACCC, which use special composite cores having minimal thermal elongation, are most likely to be attractive.

<u>Rate of sag increase with ice load</u> is determined by the modulus of the composite conductor. In reconductoring lines that experience heavy ice loading, HTLS conductors like ACCR (3M) and GTZACSR (J Power), which use full hard aluminum and steel cores, are likely to be attractive choices. The recent introduction of ACSS/TW with an ultra high strength core makes the use of ACSS more likely in high ice load areas.

<u>Installation simplicity</u> may be a very important factor in choosing the "right" HTLS conductor, especially for a small contractor or small utility with limited experience and small construction or maintenance staff. ACSS and ACSS/TW have been in use for over 30 years. There are very minor issues in installation. The installation of ACCR and GZTACSR has been carefully documented.

<u>Confidence in manufacturer claims</u> is a fundamental issue in selecting HTLS conductor. All the manufacturers of HTLS conductor have been quite careful to prove their claims of long-term physical behavior.

7
FIELD TRIAL MONITORING OF HTLS CONDUCTORS AND THEIR ACCESSORIES

Introduction

This project was intended to provide participating utilities with the necessary information on design, installation, operation, and maintenance issues. Although three years of field trial experience is relatively short compared to the life-span of the conductors, this project provides general information on how HTLS conductors operate at different current ratings and geographical locales and provides key information on design, installation and operation of selected HTLS conductors and their hardware accessories. Moreover, given that electric utilities have very limited operational experience with HTLS conductors, especially with recently commercialized conductors, this field measurement program identifies any aging and degradation problems on conductors and accessories operated at elevated temperature for a considerable period of time. Although manufacturers provide laboratory tests and installation guides for their HTLS conductors and accessories, these field tests will help utilities to validate the performance in a real system.

The basic motivation for reconductoring an existing line with HTLS conductor is to increase the thermal rating of the existing line without completely rebuilding/modifying the existing infrastructure. In each of the field-test lines, the original conductor was replaced with an equivalent HTLS conductor, and the energized line was monitored under the same operational conditions. Although HTLS conductors are expected to operate at higher current rating with increased temperature, some of the reconductored HTLS conductors at the field test sites were not necessarily operated at high temperatures because of the real-life situation at the site.

This section describes the data monitoring and instrumentation used in the field trials and the procedures for field data observations and analysis. The section also describes the four field test sites at CenterPoint Energy, Hydro One, Arizona Public Service, and San Diego Gas & Electric. A summary of the field test sites is shown in Table 7-1.

Table 7-1
Summary of HTLS Field Tests

Location	Conductor Type	Conductor Diameter (in.)	Voltage (kV)	Number of Spans	Total Length (ft)	Number of Splices
CenterPoint Energy	ACSS/TW	1.108	138	4	2280	2
Hydro One	GAP	1.108	230	4	1800	2
	Invar	1.108	230	5	1900	2
Arizona Public Service	Carbon Fiber Composite	1.108	69	4	956	2
San Diego Gas & Electric	Aluminum Composite	1.108	69	3	902	2

Data Monitoring and Instrumentation

The objective of the line monitoring program is to determine whether anomalies in these field trial sites were observed in terms of physical, electric, and mechanical properties of the HTLS conductors and their accessories while being operated at different current ratings and ambient conditions. The determination of load capacity in a high-voltage transmission network must take into account, on the one hand, the ambient conditions, such as temperature, wind speed, wind direction, and solar radiation and, on the other hand, the electric conditions of operation. This is to respect the minimum safety distances and to maintain the voltage and the network stability within suitable limits. To evaluate the thermal conditions of HTLS conductors in the test sites, physical and electrical properties of the live conductors were monitored continuously, including ambient conditions with appropriate instruments. Some of the line parameters (e.g., current, temperature, ground clearance) were monitored continuously, whereas other parameters (splice resistance, corona activities, and electromagnetic field) were monitored at regular intervals during each site visit. The description of the measurement process for each parameter is described as follows:

Current

As current is primarily responsible for increasing the temperature of the conductor, the chronological current data for HTLS conductors in each field trial site is obtained from the respective host utility. It is a common practice for utilities to monitor and record the current flowing through each transmission and distribution line in substations for a continuous period of time.

Sag and Tension

As utilities increase the electric load in their transmission lines, the conductors heat up, anneal, and sag. The ground clearance – a basis for line's rating calculation – becomes a real limiting factor as the utility has to maintain a safe clearance between energized conductors and the ground mandated by National Electric Safety Code (NESC). In this context, ground clearance needs to be closely monitored by a conductor sag monitoring device called sagometer. As the temperature of the conductor increases, the remaining ultimate mechanical strength of the conductor decreases. To avoid the failure of the conductor, the tensile load on the conductor needs to be closely watched such that the applied tensile load never exceeds the given ultimate strength of the conductor. Hence the mechanical tension and vertical clearance (i.e., sag) are continuously monitored from load cell and sagometer (see Figure 7-1). The monitoring system is equipped with a data acquisition and processing unit.

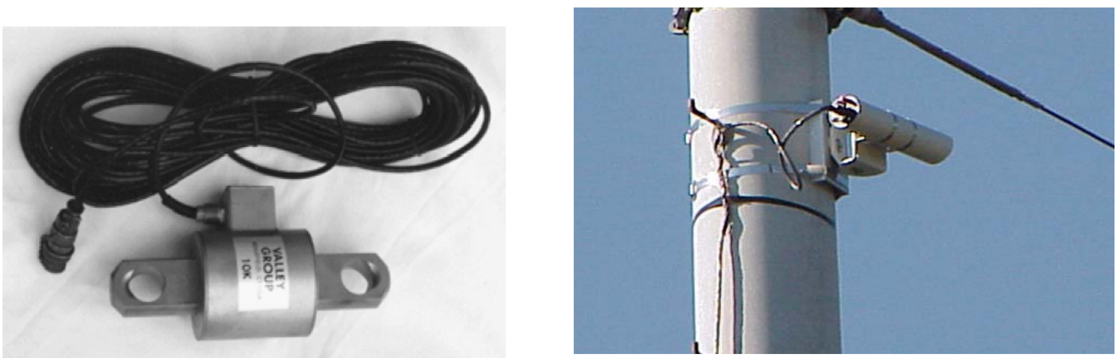


Figure 7-1
Load cell (left) (Valley Group Inc.) & video sagometer (right), at one of the field trial sites

The data acquisition is done at 1-minute intervals for all channels. The vertical clearance data is obtained from a data acquisition and analysis system, a communications system and an antenna, and the target on the line. All the measuring equipments are mounted on transmission line structures. At the time of installation, the location of the conductor or target is calibrated to the measured ground clearance. At any later time, line sag is computed by determining the new location of the conductor using image-processing techniques and the calibration constants. The resulting ground clearance information can be made available in real time using telemetry, or it can be logged for historical study. With the known relationship between sag, temperature, and the conductor, the relative sag position of the conductor at any given time from its initial position could be used to determine the temperature at which the conductor is operating at that given time.

Ambient Conditions

A conductor is supposed to operate without degrading its physical properties. The physical properties of the conductor are dependent on the level of current that it is carrying and weather conditions, especially temperature, solar radiation, wind speed, and wind direction. The lowest thermal capabilities occur when the wind speed is low and the ambient temperature and solar radiation are high. This is the reason that utilities usually design transmission and distribution lines based on a target operating temperature at a prescribed set of ambient conditions. Taking these factors into consideration, the ambient condition is measured in the field. The measurement of weather parameters is helpful to assess the conductor behavior at different ambient conditions. The ambient measurement system consists of an anemometer to measure wind speed and direction, rain gauge to measure precipitation, and a net radiation sensor and ambient temperature sensor to measure solar radiation and ambient temperature, respectively. The chronological wind speed (both two dimensional and three dimensional) are recorded from 2-D and 3-D anemometers, respectively. By monitoring transmission lines that limit transmission capability, it may be possible to increase the transfer capacity and allow increased transmission usage.

Figure 7-2
Ambient condition measurements from a set of instruments: anemometer, rain gauge etc. powered though a solar panel

Splice Resistance

The splice, which connects the two pieces of the conductor, is the weakest link of the transmission line. When two conductor pieces are joined with splices or dead-ends, the compression on splices and dead-ends over the conductor surface forms the conductance interface between the conductor surface and the inner surface of the splice fitting through the hydraulic crimping process. Because of the extra mass of the compression fitting compared to the mass of the conductor that it connects, all compression fittings should operate cooler than the conductor. This is because the added mass and diameter allow for greater heat transfer and radiation to keep them cooler. However, during the repeated process of heating and cooling, alternately at the peak and off-peak hours, the compression fitting loses its mechanical integrity, increasing the contact resistance. This may cause the interface temperature to go excessively higher than the conductor surface temperature. The temperature beyond 93ºC is very critical for ACSR conductors because outer aluminum strands start to anneal beyond this temperature.

The resistance across the splices is measured with a live line micro ohmmeter, called an "Ohmstik." The joint resistance can be measured while the line is energized. The Ohmstik measures the micro-ohm resistance of conductors, connectors, splices, and switching devices positioned directly on an energized, high-voltage line (see Figure 7-3). The Ohmstik calculates resistance by measuring the AC amperage in the line and the voltage drop due to the resistance of the line segment under test. Using the AC current in the line ensures that realistic current distributions through the connection are being measured. The instrument is pressed against the splice or connector in such a manner that the connection under the test is between the two electrodes. The conductor, for which the resistance is to be measured, is reached from the bucket truck, and the resistance is measured by placing electrodes at the mouth of the splice, and at the center of the splice. In a few seconds, the instrument is removed from the line, and the line amperage and resistance are displayed on the front panel of the display unit. This measurement helps to identify any problems associated with the integrity of splices on the conductor and helps to rectify any future problems.

Figure 7-3
Splice resistance measurement with a Sensor Link OhmStik at the site

Corona

Corona is a luminous partial discharge from current carrying conductors and insulators due to ionization of the air, where the electrical field exceeds a critical value. When conductors and insulators are exposed to high electric field, which occurs at high-voltage and ultra-high-voltage levels, the ionization takes place causing air to discharge. Corona, if not always a problem by itself, is often an indicator of a fault. Corona is an indication of contamination, like salt, on insulators. In some cases it can indicate imminent tripping. Corona is accompanied by excitation of nitrogen molecules, leading to emission of UV radiation when the electric field exceeds a critical value. The corona discharge emits radiation in the 280-405 nanometer (nm) spectral range, mostly in the ultraviolet (UV) range, and therefore is invisible to the human eye. However, relatively weak emission at about 400 nm might be observed at night under conditions of absolute darkness. The DayCor® corona camera is a bi-spectral Solar Blind UV-Visible imager, designed to detect these very faint UV emissions in the solar blind UV band, with high signal-to-background ratio.

After the initial energization of the transmission line, the test span conductor and associated hardware were viewed with a daytime DayCor® camera at different time interval during each site visit. The images were updated following each site visit during the entire field trial period. Similar procedures as presented in the EPRI "Guide to Corona and Arcing Inspection of Overhead Transmission Lines" were followed during the inspection process. Figure 7-4 shows corona images of one of the sections of newly installed HTLS conductors observed during the inspection process.

Figure 7-4
Corona observations on HTLS conductor surfaces installed in one of the field trial sites

Electric and Magnetic Field (EMF)

In recent years there has been a concern over possible adverse health effects due to electric and magnetic fields. Electric fields are created by electric charges whose strength depends on the voltage on the conductor. This means that a high-voltage power line produces a stronger electric field than a low-voltage power line. Electric fields represent the forces that electric charges exert on one another. In this context, lateral profiles of electric and magnetic field are observed at a height of 1 meter above the ground as per ANSI/IEEE standard under the transmission line. The measurements were done at mid-spans of every span of the test line along the ground surface perpendicular to the conductor line from an electromagnetic field (EMF) meter called STAR 1000™. The lateral profiles were taken along a 100-ft line perpendicular to the conductors at the mid-spans of the test line such that the 50-ft point is directly under the conductor (see Figure 7-5).

In general, the material that ACSR conductor is made up of makes no direct difference on EMF exposure level on the ground. However, there are some claims in the electric industry that some conductors will alter the electric and magnetic fields at the ground level. Therefore, EMF observation is made in order to verify this fact.

Figure 7-5
EMF measurement process under a transmission line

Infrared (IR) Measurements

In an electrical system, elevated temperature whether on insulators, conductor, splices or other accessories caused by electrical failure can lead to mechanical failure. Thus, there is a need to observe the temperature on various components of an overhead line in order to identify potential failures. Among the various line components, the fitting connecting two conductors is a critical component in terms of electrical and mechanical integrity. As temperature rises, the resistivity of the materials at the interface between the conductor strands and the aluminum sleeve increases. As the resistivity increases, the temperature of the fitting increases. This can lead to thermal runaway, which may lead to failure that could be catastrophic.

Knowing this relation, field inspections of fittings with infrared technology could be used to locate pending failures and prioritize maintenance efforts to remove or remediate at-risk fittings. Conventional maintenance rules-of-thumb indicate that a fitting that has been identified as hotter than the conductor needs replacement. To identify possible thermal runaway problems on transmission line components, especially on compression fittings, a long-wave infrared camera, fitted with a 7 degree telephoto lens set atop a tripod, is used. In these field trials, spots were painted on infrared target locations during installation of the conductor with a white-colored paint of known high emissivity to improve the accuracy of the temperature measurements while minimizing the effects from solar heating. In addition, visual photographs were taken at each target location to assist in interpretation of the corresponding infrared images. Figure 7-6 shows an IR image and the visual image of the same dead-end assembly, which assists in the interpretation of the infrared image.

Figure 7-6
Visual and IR images of a dead-end assembly on a HTLS transmission system

Visual Inspection

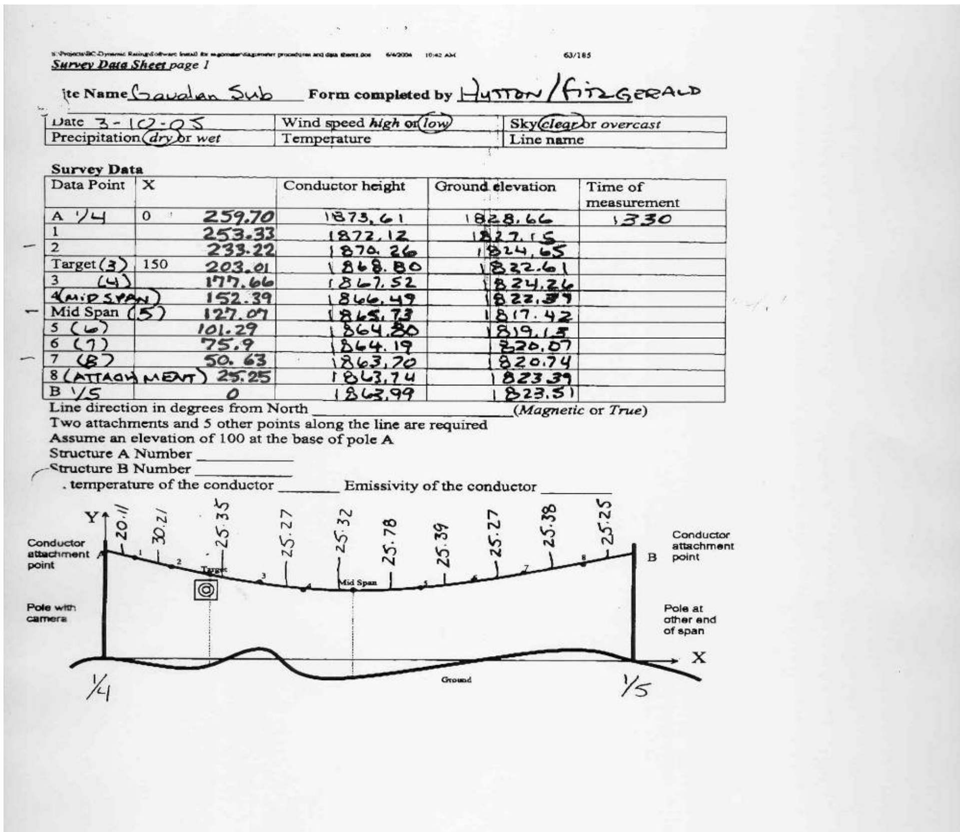
Visual inspection continues to be an important part of transmission line operation and maintenance practice, especially in high-voltage systems. In a high-voltage transmission network, problems associated with insulation failure due to various reasons, including short-circuit currents, can cause severe burn-outs. A burnout could be easily identified through visual inspection. Visual inspections of the test line are considered to be an important part of the HTLS conductor assessment. Regular visual inspections will help the project in identifying any major problems on the conductors, splices, and associated hardware.

Every site visit includes visual inspections using binoculars, camera, zoom lens and other complementary accessories as needed. Figure 7-7 shows pictures of several main components of the test segment taken during one of the site visits from a high-resolution camera.

Figure 7-7
Visual inspection along the line components of a transmission system involving HTLS conductors in one of the field trial sites

Field Survey

At least once (usually more) during each site visit, a survey is done along the ground surface underneath the HTLS conductors. A survey sheet (see Figure 7-8) is filled out by the surveyors. The data recorded include the distance at different points along a span between two pole structures, and conductor height and ground elevation at these points. The survey helps to assess the geographical profiles of a field trial site and provide important information on conductor clearance along the test line routes.


Survey Data Sheet page 1

ite Name Gaudian Sub Form completed by HUTTON/FITZGERALD

Date 3-10-05	Wind speed *high* or *low*	Sky *clear* or *overcast*
Precipitation *dry* or *wet*	Temperature	Line name

Survey Data

Data Point	X	Conductor height	Ground elevation	Time of measurement
A 1/4	0 259.70	1873.61	1828.66	1330
1	253.33	1872.12	1827.15	
2	233.22	1870.26	1824.65	
Target (3)	150 203.01	1868.80	1822.61	
3 (4)	177.66	1867.52	1824.26	
4 (MID SPAN)	152.39	1866.49	1822.39	
Mid Span (5)	127.07	1865.73	1817.42	
5 (6)	101.29	1864.80	1819.15	
6 (7)	75.9	1864.19	1820.07	
7 (8)	50.63	1863.70	1820.74	
8 (ATTACHMENT)	25.25	1863.74	1823.39	
B 1/5	0	1863.99	1823.51	

Line direction in degrees from North ______________ (*Magnetic* or *True*)
Two attachments and 5 other points along the line are required
Assume an elevation of 100 at the base of pole A
Structure A Number ___________
Structure B Number ___________
. temperature of the conductor _______ Emissivity of the conductor ________

Figure 7-8
Sample of survey data taken on a particular day between two structures

CenterPoint Energy Field Test

The test line is located on the CenterPoint Energy (CNP) transmission system designated as "138 kV Ckt 06G-3 – Jefferson Sub – Pasadena Sub (North Circuit)" in Houston, Texas (see Figure 7-9). The existing north-side circuit consisting of three phases of 2-subconductor bundle of 795 kcmil ACSR was replaced with three phases of single-conductor of 959.6 kcmil (Suwannee) ACSS/TW. The conductor was supplied by Southwire of Carrollton, GA. Installation of conductor and monitoring instruments was completed at the CNP site on May 26, 2003. The test line includes five structures with four spans in a vertical three-phase arrangement. The total length of the test segment is approximately 2,880 ft and runs east to west.

Figure 7-9
Towers and instruments installed at the CNP Energy site

Field Data Observations and Analysis at CenterPoint Energy Field Test Site

The sag and tension monitoring system is mounted on one of the transmission towers in the test line. The system monitors transmission line tension and ambient conditions that affect transmission line operating temperatures. The sag of any conductor is dependent on the coefficient of thermal expansion (CTE) of the conductor, the length of the conductor span, the height of the transmission line towers, and the tension along the conductor. The thermal expansion of any conductor depends on the conductor surface temperature. The sag is higher when the conductor temperature is higher, which takes place when the current flowing through the conductor is higher. The tension on the conductor is monitored from the load cell installed at the dead-end assembly.

Conductor core temperature with respect to ground clearance at the target was calculated based on a Power Line Systems - Computer Aided Design and Drafting (PLS-CADD) and SAG10 model, and the temperatures data curve was validated with the actual infrared measurements taken during the site inspections. These measurements show that the conductor was not operated at or beyond the critical temperature limit.

Comparing the temperature from the weather-based model (EPRI model) and the sag/tension-based model (SAG10) estimates shows a reasonably good agreement. However, it was recommended that direct measurement of conductor temperature be made to resolve subtle points of thermal model accuracy.

In addition to the continuously monitored data, frequent visits were made to the field sites to measure splice resistance across the splices just to make sure that splices were installed and hence working properly. This will identify any flaws during the installation and operation. This trend clearly indicated no abnormalities during the installation and operation process.

The electric and magnetic field profiles were measured along a 100-ft line perpendicular to the conductors at the mid-spans of the test line directly under the conductor. A visual inspection of the test line was performed. Digital pictures were taken along the test line to document the condition of the conductor, splices, and associated hardware. Infrared (IR) imaging was performed to detect any hot spots along various components of the line, including the conductor. To detect corona activity, the test span conductor and hardware accessories were also viewed thoroughly with a DayCor camera. No noticeable corona activity was observed from the DayCor camera.

Hydro One Field Test

The test line was located on a Hydro One 230-kV transmission circuit, east of Ottawa, Canada. The two outermost phase overhead conductors (1843 kcmil, 1.6-in. diameter, 72/7 ACSR) of L24A circuit was bypassed by two temporary wooden pole lines for an approximate distance of 1,600 ft (see Figure 7-10). One wooden pole line carried a single "GZTACSR" Gap type with 795 kcmil (1.108 in. diameter) Drake conductor (single phase), as shown in Figure 7-11. This Gap test segment consisted of four spans, approximately 1800 ft. in length, and included five structures (two dead-ends and three suspension poles). The other wooden pole lines carried a single Invar type with 1.108 in. diameter conductor along the five spans. The Gap GZTACSR conductor was supplied by J-Power, Japan, and the Invar conductor was supplied by LS Cable, Korea. Two splices were used for each Gap and Invar conductor in their sections. Conductors and accessories, including monitoring instruments, were installed on October 24, 2004. Existing outer-phase conductors were placed in the original condition with the intention of restoring the circuit quickly to its original physical condition to avoid any possible customer interruption.

Figure 7-10
Towers before (left) and after (right) the bypass

Figure 7-11
Zoom view of wooden poles carrying the Gap conductor

The Gap-type conductor used in the Hydro One field site is classified as “GZTACSR,” with an outside diameter of 1.108 in. and 469.5 mm^2 of total cross-section area. The conductor is concentric-lay-stranded, made from round and trapezoid super-thermal-resistant aluminum alloy wire (ZTAL) and zinc-coated extra–high-strength steel (see Figure 7-12).

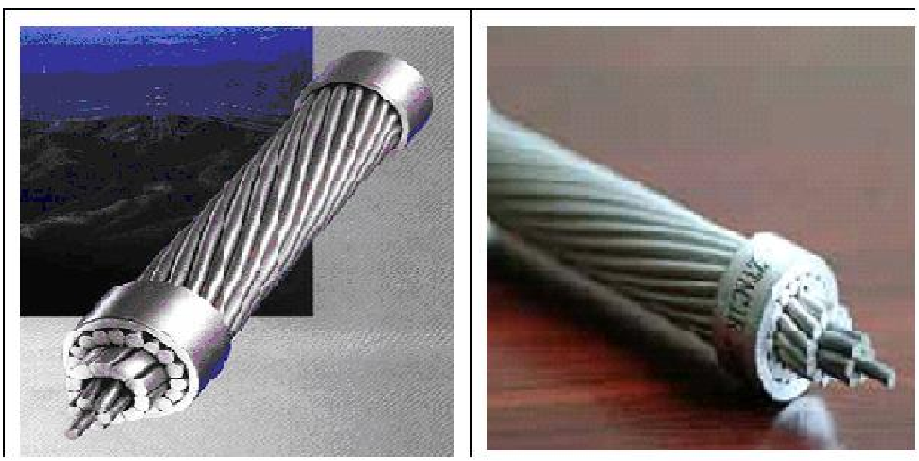


Figure 7-12
Gap (left) and Invar (right) conductors installed at Hydro One

The inner alloy layer is made from trapezoidal wires to form a tube. The installation of Gap-type conductor at the Hydro One site was the first of such installation in North America.

Invar conductor was initially developed in Japan by J-Power using a core made of invar, which is an alloy of iron and nickel (see Figure 7-12, right). Invar steel alloy wires have a reduced rate of thermal elongation and a slightly lower tensile strength than high strength steel wires. The current-carrying capacity of the invar conductor is increased by using a super-thermal-resistant aluminum alloy wire (ZTAL) on the conductor.

Field Data Observations and Analysis at the Hydro One Field Test Site (Gap)

Continuous data on sag, tension, and the weather were monitored and analyzed for the Gap and Invar conductors installed at the Hydro One site. An important and distinct observation on pole tilt was noticed at this site because of the wet ground. The higher tensile force along the conductor tends to pull the newly installed poles together; as a result, the tilt (the vertical displacement) is observed at the pole. However, this has nothing to do with this particular type of the conductor. The tilt was measured by a set of inclinometers mounted inside the sagometer's camera unit. This observation was unique for the Hydro One site because it involved the installation of new wooden poles, which were displaced from their original position because of wet ground. The temporary dead-end pole installed for the Gap conductor at Hydro One was, unfortunately, placed in a relatively wet soil and was not guyed adequately.

The line design software program – Alcoa Sag10 – predicts the sag-tension-temperature behavior. SAG10 software is well recognized as the industry standard for calculating sag and tension for most conductors. The sag-temperature curve, as obtained from SAG10 model, was validated with at least one calibration point, which was obtained at the time when the conductor was carrying close to zero load, and the solar heating was nearly absent, such as at night. At this situation, the conductor temperature is very close to the ambient temperature, and the sagometer reading gives a data set for the calibration point. As expected, the conductor temperature increases as the current through the conductor increases.

The real-time weather (wind speed, wind direction, ambient temperature, and solar intensity), along with the real-time current, can be used to calculate the real-time conductor temperature using EPRI's Dynamic Thermal Circuit Rating (DTCR) program. Real-time simulations using DTCR were performed on the Gap data on a month-by-month basis.

In addition to the continuously monitored data, regular site visits were made to the field sites to measure splice resistance across the splices. In addition to the continuously monitored data, measurements of resistance across the splices showed no definite trend.

After the initial energization, the test span conductor and hardware were viewed with a DayCor camera. Because the cable was dragged on the ground before it was hung, there was a significant amount of mud and grass imbedded on the conductor. These contaminations became corona sources when the line was first energized. Over time, it is expected that corona will cease by itself. Some discharge activities were also observed in some dead-end structures, vibration recorders, and suspension insulators.

A number of IR images were taken, and the IR observation was compared with the corresponding digital pictures. However, no abnormal temperature was observed in any parts of the line, splices, and dead-ends.

The electric and magnetic field profiles were taken along a 100-ft line perpendicular to the conductors at the mid-spans of the test line at a height 1 m above the ground. The EMF meter was oriented for the maximum reading for determining the maximum induction effect.

Field Data Observations and Analysis at Hydro One Field Test Site (Invar)

Measurement activities on tension, sag, and weather parameters (wind speed, wind direction, ambient temperature, and solar intensity) on the Invar conductor started at the Hydro One field site from October 4, 2004. The conductor current data were provided by Hydro One on a regular basis. The sag data were obtained from sagometer measurements. The average conductor core temperature was deduced from the sag data using the SAG10 model.

The data on measured ground clearances from the sagometer and the measured tensions are very complete with little data lost. This is further substantiated by the fact that the measured tensions compare closely with the tensions computed from the sag measurements. This is quite different from the data for the Gap conductor where the dead-end poles were moving. Fortunately, this does not seem to be the case for the Invar.

Electric and magnetic field measurements were made in lateral directions along a 50 foot line on both sides of the transmission line using an EMF meter (STAR 1000™) such that the reference measurement was made just below the transmission line at the mid-span.

An infrared (IR) visual inspection of the conductor and its components showed no abnormal temperature behavior. After initial energization, the test span conductor and associated hardware were viewed with a DayCor daytime corona camera. A similar level of corona observation was noticed in the Invar conductor as was observed in the GAP type. The reason could be the same as for the Gap conductor—high-voltage operation and presence of contaminations with mud and debris on the conductor surface.

Arizona Public Service Field Test

The test line was located on the Arizona Public Service (APS) 69-kV transmission system at the Gavilan Peak Substation at the extreme northern part of Phoenix, Arizona (see Figure 7-13). The existing single vertical circuit of 795 kcmil ACSR was replaced with single conductor phases of 1020 kcmil (Drake overall diameter equivalent) ACCC conductor in four spans (956 ft) of single-pole structure along the Gavilan Peak Substation to Dove Valley Substation section. The conductor was supplied by Composite Technology Corporation (CTC) of Irvine, California. ACCC conductor was installed at Arizona Public Service site in March 2005. The line was energized on June 17, 2005. Two splices were installed on the bottom phase of the test line conductor, “splice one” on the west side and “splice two” on the east side. They are located approximately at mid-span between structures 69A60 and 70-H3. Installation of monitoring instrumentation was completed on May 12, 2005.

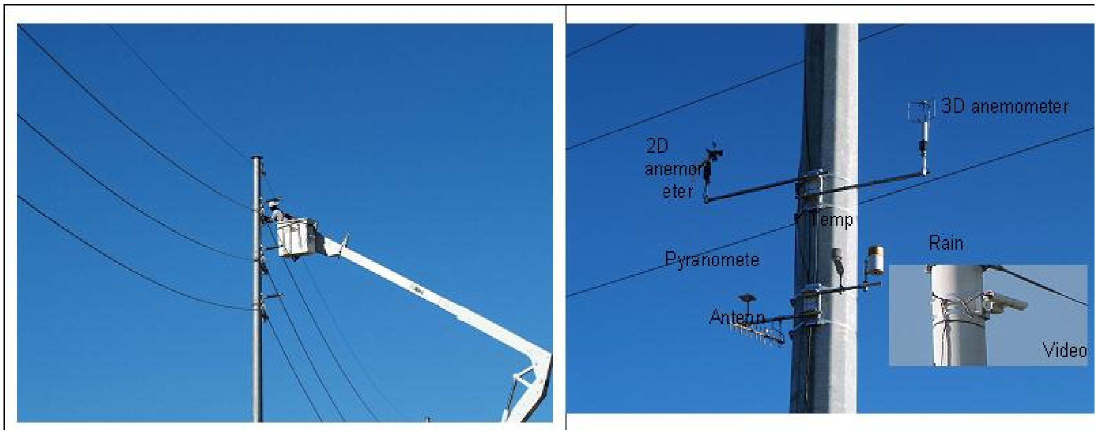


Figure 7-13
Towers and instruments installed at the APS site

The conductor used in the APS field site is classified as "Trapezoidal Shaped Concentric-Lay-Stranded Conductor" ACCC/TW with an outside diameter 1.108 in. and an aluminum cross-sectional area equivalent to 1020 kcmil (see Figure 7-14).

Figure 7-14
ACCC conductor (Suwannee) installed at APS site

Field Data Observations and Analysis at Arizona Public Service Field Test Site

The sagometer and load cells mounted on one of the transmission structures at the APS field trial site continuously monitor the sag and tensions on the conductors. Given the data on sag and clearance, SAG10 model is used to calculate the average temperature of the conductor. The tension on the conductor is monitored from the load cell installed at the dead-end assembly, whereas the sag or clearance is monitored from the sagometer. Tensions calculated from sag as measured from sagometer and measured tensions from load cells show remarkable agreement. This indicates that both measurements are good, and sag and tension can each be calculated from each other.

Faults in an electrical installation often appear as hot-spots, which can be detected by an IR camera. Hot spots are often the result of increased resistance in a circuit, which may be due to overloading in the circuit or insulation failure, which may be due to loose, oxidized, or corroded connectors. An infrared (IR) visual inspection was made of all components (i.e., dead-ends and splices), including the conductor at the site, during every site visit to detect possible temperature rise.

During each site visit, resistance measurements were taken across splices to make sure that they were installed properly, and that there was no increase in contact resistance, which can create hot spots.

Electric and magnetic field measurements were taken under the transmission line using an EMF meter (STAR 1000™) to record EMF levels. The strength of an electric field at a measurement point is dependent on the operating voltage of the line, and its value diminishes inversely to the square of the distance from the power line. No single instantaneous magnetic field measurement at a particular spot may be repeatable due to the changing current on the transmission line. Moreover, magnetic fields are altered by objects such as trees, buildings and vehicles, and by climatic conditions such as rain, making the measurements quite variable. It is to be noted that magnetic fields near most electrical appliances are usually stronger than fields directly beneath a transmission line.

Possible corona formation on the conductor and other components of the test line was monitored using a DayCor camera during the site visits in July 2005 and March 2006.

San Diego Gas and Electric Field Test

The test site was located on the San Diego Gas and Electric (SDG&E) 69-kV transmission circuit in Oceanside, North of San Diego, California. ACSR conductors of size 636 kcmil were replaced with 795 kcmil (T16, 1.108 dia.) ACCR conductor supplied by 3M of Minneapolis, MN along the three spans of the transmission line for a total length 902 ft. The towers are single-pole type, with horizontal insulators and suspension clamps (see Figure 7-15). Two splices are used in one of the three sections. Conductors, including monitoring instruments, were installed on July 21, 2005, and data were continuously collected thereafter.

Figure 7-15
SDG&E test site

The 3M conductor used in the SDG&E site is classified as "ACCR" with size 795 kcmil (1.108 in. diameter). The outer strands are composed of a temperature-resistant Al-Zr alloy, which can withstand temperature up to 210ºC continuously and 240ºC in emergency condition. The core of the conductor contains alumina fibers in an aluminum matrix (see Figure 7-16).

Figure 7-16
ACCR (3M) conductor and its cross-sectional area

Field Data Observations and Analysis at the San Diego Gas & Electric Field Test Site

Measurement activities on tension, sag, and weather parameters (wind speed, wind direction, ambient temperature, and solar intensity) on ACCR conductor at the SDG&E field site commenced on July 21, 2005 till February 2008. The conductor current data are continuously provided by SDG&E on a regular basis. The average conductor core temperature data, as deduced from the SAG10 model, are validated with actual measurements of temperature and sag, and are also compared with EPRI's thermal model. The curve obtained from the SAG10 model can also be approximated with a fourth-order polynomial curve. Sag data were obtained from the sagometer installed on the poles.

In addition to the continuous data on various parameters (current, sag, wind velocity, solar radiation, and rain), measurements of EMF, corona discharge, and temperature were also carried out on the overhead conductor and other components at different intervals during the field inspection. Overall, the IR measurements have not shown that any piece of hardware was running hotter than expected.

After energizing the transmission line, the test span conductor and hardware were viewed with a DayCor camera. Low level corona activities were observed on some of the Preformed splices and dead-end. This may be due to contaminations of dirt and debris on the Preformed splice surface.

Resistance measurements were made across two splices (Preformed and compression type) to verify their electrical and mechanical integrity. These measurements, taken during site visits from 2005 to 2008, showed random variations, but no clear trend was detected with time.

During each visit, a thorough inspection was made of the test line and its components using binoculars, camera, and zoom lens. The general observation showed that the ACCR conductor, including all the components, appeared to be normal at every inspection.

Summary and Final Remarks

Overall, continuous data monitoring and line inspection during regular site visit show that HTLS conductors in all field trial sites are behaving according to expectations. Physical observations are normal, except at the SDG&E and Hydro One field trial sites, where corona is observed. Corona can be due to contamination on the surface of conductors and other accessories under high system operating voltage. It was found that when the conductors were dragged along the ground during installation, there were significant amounts of mud and debris embedded on the surface of the conductors and other accessories. These became a corona source after the line was energized. But corona activities ceased with time as the debris on the conductor was burned off from the heat of partial discharges. The high level of corona activities observed in the case of Hydro One system may be due to high system voltage (230 kV) compared to other field trial sites. The corona level is not that high in the case of SG&E site, where few Preformed splices create corona activities due to contaminations.

A distinct observation (i.e., pole tilt) was noticed on the wooden poles of the Hydro One field trial site due to the wet ground. This observation was unique because it involved the installation of new wooden poles in wet soil to divert the current from the original conductor to the Gap conductor. These dead-end poles shifted inward from the original vertical position due to the tensile force on the wires. As a result, the observed sag, as recorded from the sagometer, was higher than the actual sag. This resulted in overestimation of average conductor temperature using the SAG10 model. The HTLS conductors at the CenterPoint Energy and Hydro One sites are running near the optimal current ratings of the conductors, whereas the conductors at the SDG&E and APS sites are running at relatively low levels compared to their ratings.

Table 7-2
Overview of the data monitoring and field observations

Field Trial Sites \ Parameters	Conductor Loading	Sag and Tension	Splice Resistance	Corona Observation	EMF	IR
CenterPoint Energy	High	Normal	Normal	Absent	Normal	Normal
Hydro One (Gap)	High	Normal*	Normal	Present	Normal	Normal
Hydro One (Invar)	High	Normal	Normal	Present	Normal	Normal
Arizona Public Service	Low	Normal	Normal	Absent	Normal	Normal
San Diego Gas & Electric	Low	Normal	Normal	Present	Normal	Normal

Note: *Sag measurements as recorded by the video sagometer were higher than estimated values due to shifting of the wooden pole structure.

8
PREDICTION OF SERVICE LIFE FOR HTLS CONDUCTORS

Introduction

One of the most perplexing questions regarding the use of HTLS conductors in existing overhead lines, concerns their service life. That is, how long will they continue to perform satisfactorily? To say the least, this is a complex question whose answer is not easy.

Overhead transmission lines are expected to function reliably for very long periods of time while fully exposed to high winds, ice storms, wind-induced conductor motions, high electrical current events, lightning strokes, and high voltage spikes produced by switching operations.

The tools available to help in predicting service life consist of laboratory and field tests prior to initial introduction of new conductors and historical maintenance/failure records which, unfortunately, can only be populated over extended periods of time.

Background & History

Power utilities have a long history regarding the probable service life of conventional conductors such as those stranded of aluminum (AAC), of copper (CU), and of aluminum reinforced with a steel core (ACSR). Utilities in North America and Europe have utilized ACSR in overhead lines for over 100 years (The design of overhead lines and application of various conventional conductors was widely discussed in the technical literature by 1920). Some such venerable lines are still in service. Based on experience, these conductors can be expected to perform satisfactorily for at least 40 years given typical designs and a wide range of weather conditions.

Other conductors made entirely of aluminum or of aluminum reinforced by steel have been introduced in the last century. ACAR and AAAC conductors were introduced in the 1960's. SDC conductor came into widespread use in Canada in the 1980's. T2 conductor was introduced in the 1970's and ACSS began to be used in 1970. Historical experience with these conductors has generally been good though certain problems appeared over time. For example, in a number of installations, ACAR conductors experienced vibration fatigue problems and SDC conductors were found to be difficult to install, repair, and seemed to have a higher than normal incidence of corrosion problems.

HTLS Conductor System Tests

Testing of transmission conductors falls into several categories – routine manufacturing tests, small scale laboratory testing of conductor systems, full scale laboratory testing, field testing in normal transmission lines, and long-term maintenance/failure data collection.

The routine manufacturing tests specified by industry standards such as ASTM and IEC establish a consistent assurance that the materials used in stranding the conductor and fabricating the hardware has the expected mechanical, electrical, and chemical characteristics. Industry standards are normally not available for new conductors but are developed as the conductor comes into widespread use.

Small scale laboratory tests are used to prove the conductor component and the composite conductor characteristics. Typically these tests include simple tensile strength, minimum elongation, conductivity, annealing, and various mechanical strand tests. Combining the component materials in a 20 to 100 ft length of stranded conductor, the tests are expanded to include stress-strain, creep elongation, vibration fatigue, self-damping, termination in clamps and splices, etc.

Full scale laboratory tests require the fabrication of stranded conductor lengths in excess of 1,000 feet. The conductor is pulled over sheaves under tension, spliced if necessary, sagged, clipped, and terminated. Measurement instruments are installed in order to record the sag-tension behavior of the conductor in response to weather and changing electrical load. The primary tests to be run in the full scale laboratory tests may vary with the claims made by the manufacturer. For example, with high temperature, low sag conductors, the tests may involve large electrical currents and the placement of multiple thermocouples along the span. For anti-vibration conductor, the tests may focus on vibration levels with the location of the test span in an area known to produce severe wind vibration.

Field tests of new conductors should only be attempted after a full series of laboratory testing has been successfully completed. The installation of the new conductor system is to be done by normal utility or contractor personnel although the manufacturer should be involved in order to assure compliance with special methods of handling and termination the conductor. The field test should involve a multiple span line section. Monitoring is useful to prove that the conductor behaves as claimed over an extended period of time. Monitoring of wind vibration, tension, sag, weather, and conductor temperature is useful though the test should be maintained for at least a year. Special handling and preparation of the novel conductor system should be documented for inclusion in the utility installation and acceptance testing practices.

All of the HTLS conductors have been tested to determine their mechanical self-damping. In general, the self-damping of ACCR and ACIR conductors are comparable to standard ACSR. G(Z)TACSR has higher self-damping than ACSR of the same Type number because of impact damping between the steel core and the inner layer of (Z)TAC trapezoidal strands. ACSS and ACCC, may have higher self-damping than ACSR if the tension in the aluminum strand layers has been reduced either by pre-stressing or by heavy ice or ice and wind loads but do not show elevated damping unless the tension level in the annealed aluminum layers has been reduced.

There is no clear evidence that the use of TW wires of any type has a significant impact on self-damping.

Higher self-damping of HTLS conductors translates into higher everyday installed tensions and lower high temperature sag. Increased initial stringing tension of HTLS conductors may be advantageous in reconductoring as long as the structure design tensions are not exceeded.

Manufacturers of HTLS conductors maintain technical data on their conductors and the results of their own laboratory tests. Section 8 compiles technical and laboratory test data for the following conductors:

- ACSS/TW (Southwire)
- G(Z)TACSR (J-Power)
- (Z)TACIR (LS Cable)
- ACCR (3M)
- ACCC (CTC)

The following laboratory tests are typical of the tests that were performed by the various manufacturers of HTLS conductors in order to prove that their product is suitable for use in power transmission lines. To help in describing each of the test procedures, specific manufacturers may be mentioned but each of the manufacturers performed all of these tests in essentially similar manners. Details of test results can be found at the manufacturer's websites.

Mechanical Laboratory Tests

The basic necessity is that new conductor systems demonstrate mechanical strength which meets or exceeds the manufacturer's claims. These tests are not unique to HTLS conductor systems but they are essential.

Tensile Elongation Test

The purpose of the tensile strength tests is to determine the ultimate strength of HTLS composite conductors or their core. The ultimate strength at ambient and high temperatures must be known so that safe operating parameters can be established. Tension tests on samples of conductor core and composite ACSS conductor confirm that the composite conductor and core can withstand over 100% of rated tensile strength.

For example, the breaking strength of GTACSR conductor was measured using 400 mm^2 GTACSR strung across a 300-m span length, with a maximum operating tensile load of 8,800 lbf. Pre-stress was applied to the steel core. When the test was carried out at several temperature levels, the test results satisfied the requirements for rated tensile strength, which take 90% of the load tensile load of the component strands.

To measure the sag-tension characteristics on the conductor, the conductor was supplied with a dc current source up to 3,000 A. It was observed that the conductor sag increased by 13% when the conductor was allowed 80% of the permissible current. The strain characteristics of ZTACIR/AW increased with temperature, as expected, at two different rates (slopes). This is due to two different expansion rates of outer aluminum wires and Invar/AW wires. It was observed that the transition temperature of ZTACIR/AW conductor was estimated to be approximately 94°C.

Also, tensile tests were performed by 3M to characterize the mechanical behavior of ACCR composite conductor. Tests were performed at the National Electrical Energy Testing, Research, and Applications Center (NEETRAC) using a 19-ft gauge length. The breaking load was determined by pulling the conductor to a 1,000-lb load, and then further loading to failure at 10,000 lbs/min. The results showed that the breaking loads for all three sets closely reached the rated breaking strength (RBS) (i.e. 31,134 lbs). Breaking loads for three laboratory sets were 102%, 100%, and 99% of RBS.

CTC did tensile testing to determine the ultimate strength of standard composite rods that are to be used in the core of ACCC/TW conductor. The ultimate strength at ambient and high temperatures must be known so that safe operating parameters can be established. A known tensile strength at several expected operating temperatures is necessary in the overall dynamic line rating, ensuring the tensile strength of the composite is never exceeded. Over 14 tests, the Drake (1020 kcmil) size standard composite rod exhibited a failure force of 39,084 ± 785 lb.

Compression Dead-End Tensile Strength

Two-piece steel and aluminum compression fittings developed by Alcoa Conductor Accessories were successfully installed and tensile-tested on ACCR. Tests showed the conductor attained the full rated breaking strength (RBS).

Other manufacturers demonstrated similar test data.

Full Tension Splice Tensile Strength

A variety of splice designs were recommended by the manufacturers. ACCR can utilize either a specially designed compression splice or a novel preformed grip. As an example of laboratory tests of full tension splices, two-piece compression joints were fitted to 477- kcmil 3M Brand Composite Conductor and then pulled to failure in a tension test. Measured joint strengths met the strength requirements of ANSI C119.4 (1998) – section 4.4.3 for full-tension connectors. The objective of the test was to verify the room temperature maximum load-carrying capability of the Alcoa-Fujikura Ltd. (AFL) Class 1, full-tension splices for 1272 kcmil ACCR conductor. The tension in the sample was increased at a rate of 5000 lbf/min until the failure occurred. The temperature of each sample was approximately 22°C during the test. ANSI C119.4 specifies that connectors should support greater than 95% RBS in a tension test. The AFL Class 1, full-tension splices for 1272 kcmil ACCR conductor meet this criterion.

Repair Sleeve Residual Tensile Strength

Alcoa Conductor Accessories compression repair sleeves were designed, manufactured, and fitted to 477-kcmil 3M Composite Conductor and then pulled to failure in a tension test. The joints held more than 98% RBS. This exceeds the requirement set forth by ANSI C119.4 (1998) – section 4.4.3 for full-tension connectors, that states the connector should hold at least 95% of the conductor's RBS.

Compression Dead-End Sustained Load Tests

3M has performed sustained load tests for dead-end connectors in accordance with ANSI C119.4. The Alcoa Fujikura Limited (AFL) dead-end sample showed no signs of problems during the load test, and exceeded RBS in a room-temperature tensile test following the 168-hour, 77% RBS sustained load period.

Single-pad dead-end was evaluated for sustained load for making mechanical connections onto 1020 kcmil ACCC Drake conductor used on overhead distribution and transmission lines for electric utilities as per ANSI C119.4. After three pulls, six samples of dead-ends met ANSI C119.4 sustained load and Class 1 full-tension requirements on 1020 kcmil ACCC Drake. The holding strength for these samples were recorded, resulting in 96.8, 111.8, and 112.5% of the conductor rated breaking strength.

Connector Sustained Load

3M contracted with NEETRAC for a connector sustained load test in accordance with ANSI C119.4. Alcoa Fujikura Limited (AFL) installed their compound compression splice designed for the 477 ACCR conductor. ANSI C119.4 requires that a splice hold 77% of the conductor RBS for 168 hours (7 days), and still hold 95% of the conductor RBS following the sustained load period. Following 170 hours at 77% RBS, the conductor failed mid-span at a load of 20,353 lbs (104.5% RBS). Therefore, the connector passes the ANSI requirement for sustained load. This test provides information on conductor stress-strain and creep characteristics. Splice elongation was measured before, during, and after the test. This “bonus” material is not required by ANSI C119.4, but is provided for information on the system performance.

Suspension Unbalanced Load

Unbalanced load tests simulate situations where neighboring spans have very different loads, which can happen due to non-uniform ice accumulation along the surface of the conductor. To mitigate this, the 3M assembly is designed to allow the conductor to slip, which then changes the sags of the adjacent spans and permits more equal tensions on the spans. In the test, a 795-kcmil suspension assembly was anchored, and a length of new, un-weathered conductor was pulled in an attempt to pull it through the assembly. Two tests exhibited no slip up to 15% RBS tension and then continuous slip at 20% RBS. Subsequent disassembly of the suspension and the conductor layers revealed no evidence of damage to the conductor or suspension components. Thus the suspension assembly provides satisfactory behavior.

Ductility Test

ACSS uses a mischmetal coating on the steel core wires to resist flaking at high temperatures. Southwire performed ductility tests on the special steel wires. Charpy Impact Test values on steel core shows that ACSS core does have as good or better performance than conventional steel.

Torsion Test

The objective of the test is to observe the mechanical performance of the conductor and core when subjected to twisting that could occur during installation.

CTC performed a test on ACCC/TW for informational purposes. The conductor was tensioned to about 4,100 lbf i.e. 10% of the conductor rated tensile strength. This tension is in the approximate range that the conductor would be pulled during installation. The conductor was twisted by hand using the lever rod. The test shows that the core can withstand 16 revolutions of twisting around its longitudinal axis without catastrophic failure maintaining substantial mechanical strength. After 16 complete revolutions of twist, a longitudinal crack appears along the length of the core. Similarly, a torsion test was performed on the whole conductor. The conductor was twisted in the opposite direction of the lay of the outer aluminum strands until some form of deformation or bird-caging occurred. A significant level of bird-caging occurred on aluminum strands of the conductor after two complete revolutions of twist on the conductor.

J-Power also studied torsional resistance of G(Z)TACSR. In two cases where 610 mm^2 GTACSR conductors were strung across a 30-m span and then subjected to tensile forces of 6,600 and 11,000 lbf respectively, tests measured the twisting torque in the central section of each of the test lines (twist angle: 10º to 80º). The results confirmed a torsional rigidity of 30-40 $kgf\text{-}m^2/rad$, which is equivalent to the value of ACSR.

Impact and Crush Tests

The objective of crush testing is to observe the damage inflicted on the whole conductor or the composite core when subjected to controlled crush loading. Both CTC and 3M performed such tests.

The ACCC/TW conductor was mounted between two plates of a crushing machine so that the lateral movement is prevented. The load is gradually increased from 0 lbf to 110,000 lbf. The Crush Test indicates that there is a significant deformation on aluminum strands after applying 51,000 lbf of crush loading. However, deformation on composite core is negligible compared to the aluminum strands.

For the impact tests, both samples exceeded their rated strength. Torsion testing demonstrated that outer aluminum layer strand failures occur well before any core strand failures. The crush test samples suffered no damage detectable by visual inspection. Evaluation of the crush test samples at 3M showed no significant damage to the metal matrix composite (MMC) core or other internal components.

Stress-strain and Creep Laboratory Tests

Stress-strain tests were performed for all HTLS conductors and stress-strain equations were developed so that sag-tension and line design calculations can be performed with software such as the SAG10 and PLS-CADD programs.

Stress-Strain Test

For example, the stress-strain behavior of 795-kcmil 3M composite conductor was determined in accordance with the 1999 Aluminum Association Standard entitled, “A Method of Stress-Strain Testing of Aluminum Conductor and ACSR.” On the conductor, the test was started at 1,000 lbs, and the strain measurement set to zero. Load was then increased incrementally to 30%, 50%, 70%, and 75% of RBS, with the load relaxed to 1000 lbs between each increase. Finally the conductor was pulled to destruction. A repeat test was performed on the core, loading to the same strains as measured in the conductor test. The polynomial equation was derived from the testing data. The stress-strain curve for a 795-kcmil conductor and its core is publicly available in 3M’s Aluminum Conductor Composite Reinforced Technical Notebook (Conductor and Accessory Testing).

Room Temperature Creep

Creep tests are time consuming and expensive yet it is crucial that the creep rate of the various HTLS conductors be known in order to predict the sag clearance of the line.

3M has successfully performed a series of tests designed to characterize the mechanical behavior of metal matrix composite (MMC) core of aluminum conductor composite reinforced (ACCR). This test is intended to provide the test data summary and conductor property coefficients for room temperature creep tests performed in accordance with Aluminum Association guidelines. Details on field test procedures and results can be found on 3M’s homepage.

CTC performed creep tests on samples of Aluminum Conductor, Composite Core –Trapezoidal Wires (ACCC/TW), Drake size conductor. Epoxy resin dead-ends were used to terminate and tension the conductor. A servo-controlled control system ensured near-constant tension for the duration of the test. The long-term tensile creep of a conductor under constant tension is taken to be the permanent strain occurring between 1 and 1,000 hours.

Core Only – High-Temperature Creep

The composite cores used in the ACCC and ACCR HTLS conductors required separate creep tests at normal and high temperature. The conventional steel stranded cores used in ACSS and GTACSR have been tested extensively in ACSR conductors.

Typical high-temperature creep tests were performed at the NEETRAC laboratory on the metal matrix composite (MMC) core strand of 3M's 477 kcmil ACCR conductor. The Aluminum Association's 1999 guide on creep testing was used as a reference, with the exception that samples were tested at 150°C and 250°C. The test results demonstrate extremely low creep at both temperatures.

Wind-Induced Motion Laboratory Tests

Transmission conductors are subject to various types of wind-induced motions. A major concern is avoiding conductor failure due to vibration fatigue. To prevent fatigue failures, everyday conductor tension is limited to modest levels and vibration dampers can be installed near the support points. Another concern is large scale ice galloping motions that can cause flashovers and mechanical damage. The following laboratory tests were performed to evaluate the probable performance of the new HTLS conductors over the life of the line.

Galloping Test

Galloping, a high-amplitude vibration that occurs in transmission lines under certain resonant conditions, was tested at Preformed Line Products' (PLP's) facilities following IEEE 1138 test procedures. In these tests, the goal was to measure the endurance limit and to characterize any damage to suspension hardware or conductor. A length of 795-kcmil 3M composite conductor was terminated at each end using helical-rod dead-end assemblies with a helical-rod suspension assembly at a 5° turning angle in the center. This arrangement produced two spans, each of 82 ft (25m). The conductor was held under a constant tension of 25% RBS. An actuator created low-frequency (1.8 Hz) vibrations and produced a maximum vibration amplitude of 39 in. (1 m). In the test, 100,000 cycles were successfully completed with no damage to either the conductor or suspension hardware. The conductor was disassembled for visual inspection, which further indicated no damage.

Aeolian Vibration & Fatigue Testing

The purpose of this testing is to demonstrate that the conductor is normally resistant to fatigue failure and to determine the level of supplemental damping required to protect the conductor system when subjected to dynamic, wind-induced bending stresses.

Laboratory aeolian vibration testing at higher levels of activity than found in the field is commonly used to demonstrate the effectiveness of accessories under controlled and accelerated conditions. The only published industry test specification for aeolian vibration testing is for vibration testing of Optical Ground Wire (OPGW). This specification is IEEE 1138 and was adopted for the testing of both ACCC and ACCR.

In tests performed by 3M, using a vibration shaker, a 20-m sub-span of 795 kcmil ACCR was tensioned to 25% RBS using a beam/weight basket, and maintained at a vibration frequency of 29 Hz, and an antinode amplitude of 0.37 in. peak-to-peak (one-third of conductor diameter), for a period of 100 million cycles. Visual observations were made twice daily of the conductor and the suspension assembly (5° turning angle) during the test period. At the completion of the test period, the suspension assembly was removed and carefully inspected for wear or other damage. The section of the conductor at the support assembly was cut out of the span and dissected to determine if any wear or damage had occurred to the Al-Zr outer strand, the aluminum tape, or the composite core. After 100 million cycles of severe aeolian vibration activity, there was no wear or damage observed on the components of the suspension assembly or on any of the conductor constituents.

In tests performed by J-Power, 410 mm^2 GTACSR conductors (without any corrosion-resistant grease in their gap) were forcibly subjected to 2 $x10^7$ vibrations at 20.3 Hz, with maximum amplitude of 23 mm. The results showed no abnormalities other than the generation of very small amounts of black powder due to the friction of the aluminum with the steel core.

In assessing the fatigue performance of ACCC/TW conductor, the procedure described in IEEE 1138 (intended for aeolian vibration testing of overhead fiber optic ground wire) was implemented. After completion of 100 million vibration (peak to peak amplitude 0.449 in.) cycles on the conductor by a shaker, there was no sign of physical damage on aluminum strands or the core material. Unfortunately, the active dead-end sample for the conductor failed prematurely when tension tested to determine the remaining pullout strength.

Fatigue endurance of TAL and ZTAL, full-hard, zirconium alloy aluminum strands, is similar to that of ordinary 1350-H19 aluminum wires. Annealed aluminum strands (used in ACSS and ACCC) are slightly more prone to fatigue breaks than full-hard H19 aluminum strands of the same diameter but are typically at very low tension levels when the composite HTLS conductor is pre-stressed.

Self Damping Test

ACSS (and ACCC) may have higher self-damping than ACSR if the tension in the aluminum strand layers has been reduced either by pre-stressing or by heavy ice or ice and wind loads. If not pre-stressed, however, high initial tension levels may lead to premature failure from vibration fatigue unless dampers are installed.

There is no clear evidence that the use of TW wires of any type has a significant impact on self-damping.

The damping performance of ACSR and ACSS conductors varied considerably after stretching the conductor and allowing settling down to its original condition. The damping performance of ACSS and ACSS/TW conductors were superior compared to the ACSR and ACSR/TW conductors. However, there was no noticeable difference on damping performance between ACSS and ACSS/TW conductors. The damping of ACSS and ACSS/TW conductor was so great at 25 Hz that it became difficult to measure the vibration. The damping performance of all ACSR, ACSR/TW, ACSS, and ACSS/TW conductors were similar up to 20 Hz in the initial state.

Elevated Temperature Laboratory Tests

HTLS conductors are intended for use at temperatures in excess of 200°C. These tests are intended to show their ability to perform appropriately at high temperature without deterioration.

Temperature Rise Test on Suspension Clamp

The purpose of the laboratory test is to check if the temperature of the insulator's cement rises to values higher than its critical temperature, of above 100ºC. It is readily observed that, in the worst case, the replacement of the conductor introduces a temperature increase of 25ºC, approximately in the critical region of the insulator by comparison with the ACSR conductor. The critical region has been assessed as an insulating portion between socket eye and ball eye. The temperature recorded at the critical zone has been identified to be 60ºC. Thus, the highest temperatures attained anywhere in the insulator do not preclude it from working correctly.

Temperature rise Test on Compression Dead-end Clamp

The test consists in connecting 26' (8m) of Gap conductor, held up by means of a clamp system, to the terminals of a current source. The current source feeds a current to increase the conductor temperature until it reaches the maximum continuous working temperature. Simultaneously, by means of thermocouples, the temperature in different points of the dead-end clamp system is measured. It can be observed that the conductor temperature decreases in various points of the dead-end clamp. This effect is a consequence of Joule effect, which is due to the heat produced due to the flow of current and is lower than in the conductor. On the other hand, the surface available for heat dissipation is higher than in the conductor (increases natural convection). The test result shows that that the temperature on the limit of the ball socket is about 70ºC, which is lower than its critical temperature (i.e., 100ºC). Thus, it can be ensured that this temperature does not affect the correct functionality of the dead-end system.

The objective of the test was to determine if the tensile strength of the conductor/dead-end clamp system was adversely affected after being subjected to sustained elevated temperature at a constant tensile load. The conductor was tensioned to 4,670 lbf, or 15% of the cable RBS (31,134 lbf) and heated to 240ºC. This condition was maintained for 168 hours (7 days). At the end of the 168 hours, the cable was unloaded, allowed to cool naturally to room temperature and then tensioned to failure. The dead-end failed at 103% RBS, indicating that the dead-end sustained full load after being subjected to the high temperature.

Suspension Assembly Elevated Temperature Test

As with terminations and joints, it is necessary to understand the temperature difference between the conductor and the suspension assembly to ensure the assembly retains its strength. In this test, the conductor was heated to 240°C under a tension of 15% RBS for 168 hours. Using embedded thermocouples, the temperature profile was continuously monitored at the elastomer insert for a 795-kcmil 3M composite conductor. The suspension assembly was at 54°C when the conductor was at 240°C. Based on this temperature information and the rating of the elastomer material to 110°C, it is believed that these materials have sufficient durability at the maximum temperatures at which the suspension assembly operates.

Dead-End High-Temperature Sustained Load

The objective of the test was to determine if the tensile strength of the conductor/dead-end clamp system was adversely affected after being subjected to sustained elevated temperature at a constant tensile load. A 3M conductor was tensioned to 4,670 lbf, or 15% of the cable RBS (31,134 lbf) and heated to 240ºC. This condition was maintained for 168 hours (7 days). At the end of the 168 hours, the cable was unloaded, allowed to cool naturally to room temperature and then tensioned to failure. The dead-end failed at 103% RBS, indicating that the dead-end sustained full load after being subjected to the high temperature.

Compression Hardware – Current Cycle Tests

NEETRAC performed qualification tests on connectors for 795 kcmil 3M Brand Composite Conductor in its laboratory. A total of 21 compression connectors supplied by Alcoa Conductor Accessories (ACA) were connected in a series loop with 795 kcmil 3M Composite Conductor. The ANSI C119.4 methods and acceptance criteria were modified to reflect the operating temperature limits for the 3M Composite Conductor. All connectors performed well after 500 cycles from room temperature to 240°C. After meeting the ANSI 500-cycle criteria, the connectors were subjected to an additional 100 cycles at 300°C. All connectors successfully survived without any physical deterioration. One splice was installed using an experimental ACA high-temperature inhibitor compound. That sample ran marginally cooler than the identical connectors with standard filler compound.

Electrical Laboratory Tests

HTLS conductors must function in the presence of very high electrical stress levels. These tests are intended to demonstrate that the HTLS conductor will carry current with predictable electrical resistance and that it will withstand the electrical impact of arcing and corona.

Resistance

Conductor resistance is a major factor in overhead line ampacity. Nominal resistance is calculated in accordance with ASTM or other conductor specifications, using requirements for the size of the conductor components, resistivity of conductor materials, and stranding lay lengths. Direct measurement confirms the 3M Composite Conductor resistance is in accordance with nominal specifications. The 477 kcmil Composite Conductor measures 1.0 and 1.7% lower than the 3M specifications, depending on the measurement method.

Lightning Arc Test

The objective of the Lightning Arc Test performed by 3M is to compare the physical performance of ACCR conductors to ACSR conductors of equivalent aluminum alloy areas (i.e., kcmil) when subjected to increasing levels of lightning energy. Possible damages to conductors due to lightning arcs, including breakage and/or melting of the aluminum strands, are monitored. Splattering of melted metal may also cause damage to neighboring strands that are not directly affected by the arc. Ultimately, loss of tensile strength of the conductor is evaluated. Arcs are similar to lightning in that the current flows through a channel of ionized air. Each arc strike was conducted, the conductor sample being progressively tested along the length under various conditions of charge transference (current x duration). Charge transference ranged from nominally 50 coulombs to 200 coulombs. Typically currents are 100 – 400 amps and typically durations are 200-500 msec. When comparing the damage to both sizes of ACCR and ACSR conductors for all test levels, the visual assessment does not show that one performs better or worse than the other for the same size conductor.

The damage for all tests on both the 477 and 795 kcmil conductors was limited to the outer aluminum layer. There were no observations of damage to the inner aluminum layer or to the core. The 477 kcmil ACCR and ACSR conductors sustained more damage than the 795 kcmil ACCR and ACSR conductors for comparable energy levels. The 795 kcmil aluminum strand diameter (0.1749 in.) is larger than the 477 aluminum strand diameter (0.1355 in.). The smaller diameter wires are more vulnerable to damage.

High-Voltage Corona (RIV)

Testing was conducted by 3M to determine radio-influenced voltage (RIV) noise on a dead-end and on a mid-span splice joint. The ends of the helical rod had a standard “ball-end” finish. No noise (corona onset) was detected up to 306 kV (phase to phase) for the splice/joint in a single conductor configuration. The dead-end had a corona onset at 307 kV (phase to phase) for a single conductor configuration.

Short-Circuit Performance Test

The objective of the Short-Circuit Test is to observe the thermal and mechanical performance of HTLS conductors when subjected to increasing levels of short-circuit energy. Possible damages to conductors due to short-circuit currents are annealing and bird-caging of the aluminum strands. The conductors are subjected to increasing levels of short-circuit energy, as expressed by kA^2-sec, until physical damage, such as bird-caging or melting of the aluminum strands or clamps, is observed. The maximum temperatures in each conductor were recorded after each shot.

Weathering Laboratory Tests

Transmission conductors are intended to survive the effects of weather for at least 40 years without excessive deterioration. These tests are particularly important with regard to new materials such as the composite cores in ACCC and ACCR.

Corrosion Test

Stressed metals in a corrosive environment can exhibit stress corrosion characteristics. A sample of ACSS conductor was bent in a 4 in. diameter and subjected to a circulating sodium chloride solution for five weeks duration. No evidence of stress corrosion was observed.

The Salt Spray Corrosion Test was performed by CTC using an environmental chamber that complied with ASTM B117-03, standard practice for operating Salt Spray Apparatus. The objective of the Salt Spray Corrosion Test was to observe the effects on the whole conductor and the composite core of the ACCC conductor when exposed to a salt spray atmosphere for 1,000 hours. The salt-spray test shows that there is no major sign of discoloration or deterioration at the surface of the inner aluminum layer and core. However, there is an indication of dull color and discolored patches over the surface of the conductor.

Ultraviolet Light Exposure Test

The Ultraviolet Light Expose Test is to assess the mechanical performance of the ACCC/TW conductor core when exposed to ultraviolet (UV) radiation for an extended period of time. When bird-caging occurs on the surface of the conductor, the core is exposed to the sunlight. UV exposure on the core surface for an extended period of time can deteriorate the chemical properties of the core, ultimately deteriorating the mechanical strength of the conductor core. To assess the potential damage to the composite core from UV, composite samples were exposed to sunlight for approximately 324 hours, and the tensile strength was measured after exposure to determine the retained strength. The tensile test on exposed core did not show any degradation in its mechanical strength, though the surface shows some less reflective surfaces after exposure to the sunlight.

Installation Tests in the Laboratory

ACSS, ACSS/TW and ACIR can be tension strung, spliced, and terminated using compression fittings which are quite similar but longer than those used with ordinary ACSR. Of course, single stage splices and terminations are not suitable for HTLS conductors as the steel core must be gripped separately and the aluminum tubing used in ACSS and ACSS/TW splices and terminations is both annealed and somewhat longer than those used for ACSR.

There are a few problems associated with the installation, operation, and maintenance of ACSS conductors and their accessories. A CIGRE study indicates that there have been occurrences of minor wire damage and bird-caging on some ACSS conductor installations (CIGRE, 2003). In addition, there have been some performance issues at splice locations with ACSS conductors.

Because aluminum strands on ACSS conductors are annealed, they require rubber-lined stringing blocks to avoid damage to the aluminum wires. The conductor may also need to be pre-tensioned.

Overall, ACSS/TW conductors can be installed using conventional equipment and installation procedures, as recommended in IEEE Standard 524 "IEEE Guide to the Installation of Overhead Transmission Line Conductors." A bull wheel tensioner with a bottom grove diameter approximately 35 times the conductor diameter is recommended. A Stringing Sheave bottom grove diameter of 20 times the conductor diameter is recommended, however, the minimum stringing sheave diameters recommended in IEEE Std. 524 are acceptable (Thrash 2001).

The installation, splicing and termination of G(Z)TACSR is notably more complex than ACSR. The outer layers of aluminum wires must be unstranded at the termination to allow gripping the steel core and untensioning the aluminum wire layers. Also, in order to assure the free movement of the steel core relative to the aluminum layers after installation, a special type of suspension clamp must be installed at every 3 tangent structures.

Splice Sheave Criteria Test

The objective of the tests is to determine, in an indoor laboratory, the threshold combination(s) of sheave size(s), conductor angle(s) over sheave, and conductor tension(s) that cause breakage of the core wires on 590TW kcmil 3M Composite Conductor (ACCR/TW) during a single-pass test. The test conductor was strung over the sheave wheel and tensioned using pulling grips. Both ends were attached to a motor-driven, chain link loop system. The test was carried out in a temperature-controlled laboratory at 21ºC ± 2ºC. All four sheaves tested reached 25% of the conductor RTS at a specified break-over angle with no damage to the conductor. The 25% RBS tension was sustained by using a 24-in. diameter sheave for a 45° break-over angle, a 18-in. diameter sheave for a 33° breakover angle, a 16.75-in. diameter sheave for a 20° break-over angle, and an 8-in. diameter sheave for a 12° break-over angle. This test provides useful angle-per-sheave information for the design and further testing of sheave and multi-sheave configurations for 590TW ACCR.

CTC conducted the Splice Sheave Criteria Test on its 1020 kcmil ACCC/TW conductor. The test conductor was strung over the sheave wheel and tensioned using pulling grips. After 10 passes, there is a severe separation and deformation at the outer aluminum layer. A very moderate separation is observed at the inner aluminum layers.

Radial Impact Test

The objective of this test is to observe damage inflicted on the conductor surface due to impact load. The mass was raised to a certain height and released to impact directly at the surface of the conductor. A number of impact tests were performed on the CTC conductors in a combination of heights, masses, energies, and impacts used for impacting on the whole conductor and the core only. A similar test is repeated for 795 kcmil conductor as well. The damage to the aluminum strands of the ACCC conductor was more severe than the damage to the ACSR conductor. This is not surprising because the aluminum wires of ACCC conductor are fully annealed compared to the hard-drawn wires of ACSR conductors.

9

COMPARISON OF HTLS CONDUCTOR SOLUTIONS FOR IEEE LINE UPRATING TEST CASE

In 2005, the IEEE Towers, Poles, and Conductors Subcommittee 15.11, arranged a panel session during which the various manufacturers of HTLS conductors presented their solutions to a common uprating design problem. Though the design problem is not terribly similar to any of the field installations in this study, the solutions offered by the HTLS conductor manufacturers yield some useful insight into effective methods of increasing line thermal ratings by reconductoring with a HTLS conductor.

The Line Uprating Problem

The existing double circuit, 115 kV line has 26/7, 795 kcmil (403 mm^2) phase conductors. The structures are double circuit, steel lattice with concrete foundations as shown in the photograph. It was built in 1955 so it is about 50 years old. The structures and foundations are in excellent condition.

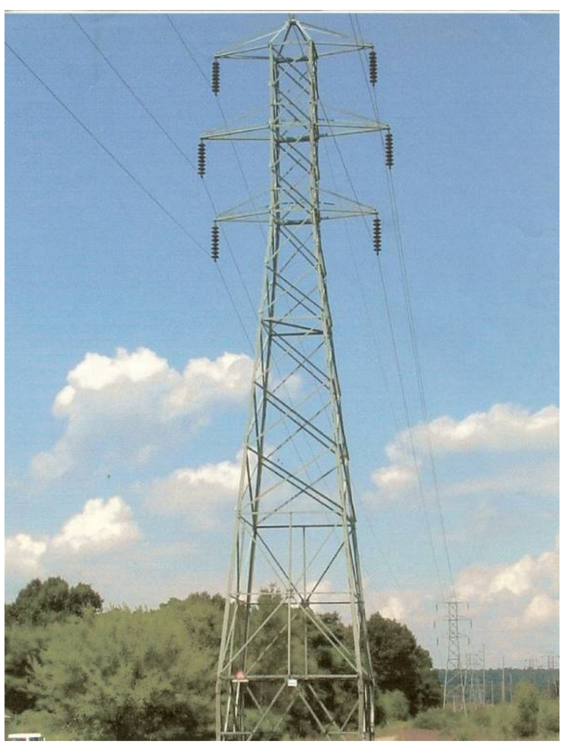


Figure 9-1
Photograph of Line Chosen as Uprating Design Case

The line sections to be reconductored have a ruling span of 1,000 feet (305 m) with individual spans ranging between 800 and 1,100 ft (244 and 335 m). The terrain through which the line passes is reasonably level. The line is relatively straight with a dead-end structure placed about every 10 spans.

Based on survey measurements, the Drake ACSR is calculated to be at a tension equal to 18% of its Rated Breaking Strength (RBS) at 60^{o}F (16^{o}C).

The original and present design loading conditions include a maximum ice loading of 1 inch (25 mm) radial ice at 32^{o}F (0^{o}C). The line clearance was originally determined by the conductor sag at 120^{o}F (49^{o}C) with a 4.5 ft (1.5 m) buffer. Present minimum electrical clearance requirements are the same as at the time the line was built.

In 1982, an asset manager discovered the generous clearance buffer of 4.5 ft (1.5 m) and the maximum conductor temperature was increased from 120^{o}F (49^{o}C) to 167^{o}F (75^{o}C). This increased the allowable high temperature ruling span sag from 25.4 ft to 28.3 ft using up most of the buffer. At 167^{o}F (75^{o}C), the summer rating is 880 amps with an assumed perpendicular wind speed of 3 ft/sec (0.91 m/sec), full sun, and an air temperature of 95^{o}F (35^{o}C).

Additional information about the line and its environmental conditions are:

- Altitude of the sun (Hc) = 71 degrees, corresponding to 42nd parallel at 12 noon on July 1st
- Azimuth of the sun (Zc) = 180 degrees, corresponding to a 12:00 noon condition where the sun is
- Total solar and sky radiated heat (Qs) = 95 W/ft^2 (1023 W/m^2)
- Azimuth of the line (Zl) = 270 degrees, corresponding to a line running East / West direction.
- Atmosphere: Clear
- Altitude of line: 0 ft above sea level
- Power Frequency: 60 Hz
- Wind Speed: 3 ft/sec (0.9 m/sec)
- Wind Direction: 90 degrees to line
- Solar Absorptivity Coefficient = 0.5
- Emissivity Coefficient = 0.5

The original line had vibration dampers installed, one per span. Over the 50 year life of the line, a few broken strands were discovered under suspension clamps.

The conductor sag with 1.0 inch (25.4 mm) of ice at 32^{o}F (0°C) and no wind is 29.1 ft (8.84 m). The complete original line design sag-tension calculations are included in the following table.

ALUMINUM COMPANY OF AMERICA SAG AND TENSION DATA
Uprating Case Study - Original Conductor Sag-Tension Data
IEEE TP&C Subcommittee
Conductor: DRAKE, 795.0 kcmil, 26/7 Stranding, ACSR
Area = 0.7264 Sq. in, Outside Diameter = 1.108 in, Weight = 1.094 lb/ft, RTS = 31,500 lb
Data from Chart No. 1-537 Aluminum Compression was calculated
Span = 1000.0 feet NESC Heavy Load Zone
Creep is NOT a Factor Rolled Rod

Design	Points					Final		Initial
Temp	Ice	Wind	K	Weight	Sag	Tension	Sag	Tension
(°F)	(in)	(psf)	(lb/ft)	(lb/ft)	(ft)	(lb)	(ft)	(lb)
0.	.50	4.00	.30	2.509	23.91	13142.	23.02	13650.
						7263.A		7937.A
						5879.S		5713.S
32.	1.00	.00	.00	3.715	29.08	16026.	29.08	16026.
						8741.A		8741.A
						7284.S		7284.S
32.	.50	.00	.00	2.094	24.12	10877.	22.21	11807.
						5479.A		6879.A
						5398.S		4927.S
-20.	.00	.00	.00	1.094	16.04	8532.	13.52	10120.
						4560.A		6519.A
						3972.S		3601.S
0.	.00	.00	.00	1.094	17.39	7875.*	14.40	9506.
						3925.A		6077.A
						3950.S		3429.S
30.	.00	.00	.00	1.094	19.43	7047.	15.83	8646.
						3074.A		5428.A
						3973.S		3219.S
60.	.00	.00	.00	1.094	21.48	6379.	17.39	7874.
						2323.A		4805.A
						4056.S		3069.S
90.	.00	.00	.00	1.094	23.48	5837.	19.03	7195.
						1653.A		4215.A
						4184.S		2980.S
120.	.00	.00	.00	1.094	25.43	5392.	20.73	6607.
						1044.A		3661.A
						4348.S		2946.S
167.	.00	.00	.00	1.094	28.34	4841.	23.43	5850.
						183.A		2860.A
						4659.S		2990.S
212.	.00	.00	.00	1.094	30.04	4569.	25.97	5279.
						-24.A		2159.A
						4593.S		3120.S
257.	.00	.00	.00	1.094	31.42	4370.	28.45	4822.
						-55.A		1510.A
						4425.S		3313.S
302.	.00	.00	.00	1.094	32.78	4190.	30.83	4452.
						-85.A		899.A
						4275.S		3553.S

* Design Condition

Power System Requirements

The utility's System Planning Department has recently concluded that the thermal rating of the line must be increased from 880 amps to at least 1350 amps continuous. While this increase in line rating is presently adequate, the planners would be willing to invest additional capital if the line rating could be made 1,500 amperes or more to avoid the need for future upratings or line replacement.

Rebuilding the line or increasing the tower height is not considered an option since this would extend outage times and require an extensive series of public hearings. The best option appears to be re-conductoring the existing line with a new High Temperature, Low Sag conductor since the original conductor is 50 years old and has experienced some vibration fatigue damage even with vibration dampers in every span. Whatever the uprating method selected, the following design constraints must be met.

Reconductoring and Uprating Design Constraints

To meet minimum electrical clearance requirements, the maximum conductor sag cannot exceed 30 feet (9.14 m) under either high temperature or ice load conditions (i.e. 1.0 inch or 25.4 mm of ice, 32ºF or 0°C, no wind). This is equal to the final sag of the original Drake ACSR conductor at 100^{o}C.

The maximum tension of the HTLS replacement conductor cannot exceed the original maximum tension - 16,000 lbf (72,435 N) - by more than 5% nor can its outside diameter exceed the original conductor diameter of 1.108 in (28.1 mm) by more than 5%.

The vertical weight of an iced replacement conductor cannot exceed the original Drake iced conductor by more than 5% and the replacement conductor must avoid worsening the vibration fatigue problems.

In responding to this request for HTLS reconductoring proposals, the HTLS conductor suppliers are asked to provide the following information:

- A table listing the key properties of the proposed HTLS conductor
- Graphs showing the Final Sag and Final Tension vs. Conductor Temperature comparing the original
- 795 kcmil Drake ACSR with the proposed HTLS conductor
- An estimate of the line's thermal rating (i.e. maximum electrical current) at the maximum allowable temperature of the replacement conductor for this study
- A description of the hardware and installation method that would be used to install the conductor.
- Any other relevant information specific to the proposed HTLS conductor Physical Constraints (Save the structures)

Discussion of the ACSS Conductor Solution – General Cable

Design proposals were presented by each of the HTLS conductor manufacturers. Their comments, suggestions, and analysis of the design problem were similar but, of course, the HTLS conductor suggested depended on the manufacturer. The following detailed discussion on the use of ACSS (as originally presented by Mr. Gordon Baker of General Cable) was typical but more detailed than most. Of course it emphasizes the advantages of ACSS and ACSS/TW which are manufactured by General Cable.

Two candidate ACSS conductor designs have been proposed as possible solutions for the reconductoring problem. Figures 1, 2, 3 and 4 provide an indication of the physical and electrical properties of these conductors. 795 kcmil MALLARD ACSS TW (22/19) is the first choice. It will meet all of the defined design conditions including the 1,500 A enhanced ampacity rating. 795 kcmil DRAKE ACSS ULMS TW (26/7) conductor, is also a possible candidate. This design however, utilizes an ultra high strength steel core material.

There are a number of reasons why the MALLARD ACSS TW conductor was selected. a) ACSS can operate at high temperature without problems. b) The 795 kcmil size was retained in order to facilitate the ampacity rating and enable lower line losses. c) The TW (trapezoidal) configuration was chosen to reduce effect of the wind and ice loading. d) The “30/19” Type 23 (ratio of the aluminum to steel cross-sectional area) conductor chosen to provide high strength and maximize the sag and tension performance. The conductor utilizes regular strength steel to help reduce the overall conductor cost.

Using the same ampacity calculation weather assumptions and conductor surface parameters as with the original DRAKE ACSR, the calculated MALLARD ACSS/TW conductor temperature for 1350 amperes is 129°C (264°F). The calculated conductor temperature for 1,500 amperes is 154°C (309°F). Using the same sag and tension calculation parameters established for the DRAKE ACSR and the limits set by the utility, the MALLARD ACSS/TW conductor would achieve a final sag of 28.49ft @ 0°C (32°F)/1”ice; 26.75 ft sag @ 129°C (264°F); and 28.20 ft sag @ 154°C (309°F).

The DRAKE ACSS ULMS TW conductor design has been included to demonstrate a potential enhancement feature for ACSS. Because the steel component represents the bulk of the strength component in an ACSS conductor, in order to bump up the Conductor Rated Strength, a stronger grade of steel is required. It has been proposed that Extra High Strength, or Ultra High strength steel be utilized in ACSS conductors.

DRAKE ACSS TW built with Regular Strength (GA or MA) or High strength (HS or MS) steel will not meet the 30ft maximum sag limit for the 1” ice loading condition. If however, you were to build the conductor with the Ultra High strength steel, the ensuing conductor sag and tension calculations resulted in meeting all of the sag requirements.

Using the same ampacity calculation parameters established for the DRAKE ACSR, the calculated DRAKE ACSS/TW conductor temperature for 1,350 amperes is 133°C (271°F). The calculated conductor temperature for 1,500 amperes is 158°C (316°F). Using the same sag and tension calculation parameters established for the DRAKE ACSR and the limits set by the utility, the DRAKE ACSS/ ULMS/ TW conductor would achieve a final sag of 29.87ft @ 0°C (32°F)/1"ice; 26.36 ft sag @ 133°C (271°F); and 27.71 ft sag @ 158°C (316°F).

Figure 1 - Comparison of Physical Properties

Conductor	Area (kcmil)	Nominal OD (in)	Nominal Mass (lb/kft)	Vertical Mass @ 1" ice (lb/ft)	Maximum* Line Tension (lb)	Cndr Type	RTS (lb)
DRAKE ACSR with regular strength steel	795	1.108	1.093	3.715	16026	16	31500
MALLARD ACSS / GA / TW	795	1.046	1.234	3.778	16832	23	34300
DRAKE ACSS / ULMS** / TW	795	1.010	1.091	3.591	15081	16	30300
Maximum Limit	-	1.163	-	3.90	16800	-	-

* based on the previously defined sag and tension criteria, NESC Heavy, 1" ice loading, etc
** ULMS is an Ultra High Strength Steel, Zinc-5%Aluminum Mischmetal coated steel core wire. This grade of steel is under review by Bekaert Steel for commercial introduction. Initial introduction may be in Europe.

Figure 2 - Power Loss and Sag Comparisons

	conductor * temperature	ac conductor resistance (ohm/kft)	I^2R Power losses/phase (kW/mile)	Sag‡ (ft)
795 DRAKE ACSR with Regular Strength steel	@ 880A 75C	0.02594	106	28.3
	@ 1350A (127C)	0.03087	297	-
	@ 1500A (153C)	0.03303	392	-
	@ 1" ice @ 0C	-	-	29.1
795 MALLARD / ACSS / TW with Regular Strength steel	@ 880A 75C	0.02557	103	23.6
	@ 1350A 129C	0.03019	291	26.8
	@ 1500A 154C	0.03233	384	28.2
	@ 1" ice @ 0C	-	-	28.5
795 DRAKE / ACSS / TW with Ultra High Strength Steel	@ 880A 76C	0.02578	105	23.2
	@ 1350A 133C	0.03062	294	26.3
	@ 1500A 158C	0.03277	389	27.7
	@ 1" ice @ 0C	-	-	29.9

maximum sag = 30ft

* based on the previously defined environmental conditions, 35C ambient, with sun and wind, etc
‡ based on the previously defined sag and tension criteria, NESC heavy, 1" ice loading, etc

Figure 3 - Maximum Amp Rating @ 30ft Sag

	conductor * temperature	conductor ampacity rating
795 kcmil DRAKE ACSR with Regular Strength steel	?	?
795 kcmil MALLARD / ACSS / TW with Regular Strength steel	185C (365F)	1655 A
795 kcmil DRAKE / ACSS / TW with Ultra High Strength Steel	200C (392F)	1700 A

* based on the previously defined environmental conditions, 35C ambient, with sun and wind, etc
30 ft sag (final condition) is based on the previously defined sag and tension criteria, NESC heavy, 1" ice loading, etc

Figure 4

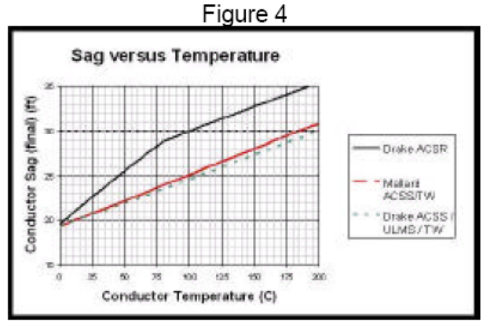


Figure 9-2
Summary of ACSS Line Uprating Analysis (Courtesy Gordon Baker, General Cable)

ACSS conductors are not a new conductor design. Since 1974, there are now thousands of miles of this conductor in operation. There is a very successful track record established. ACSS is included in the IEEE publication #524 - IEEE Guide to the Installation of Overhead Transmission Line Conductors. Deadends, Splices, Suspension Clamps, etc… and other associated high temperature hardware devices are available from multiple North American manufacturers.

ACSS and ACSS/TW conductors provide efficiency for today's new line designs. ACSS and ACSS/TW conductors enable viable line reconductoring alternatives. ACSS and ACSS/TW provide growth capacity for future needs. The utility's choice in using the 795 Mallard ACSS/TW conductor would be a wise investment in meeting their future needs.

Summary of HTLS Alternative Solutions

Each manufacturer presented their own solution to the uprating problem utilizing their type of HTLS conductor. All the HTLS suppliers were able to meet the reconductoring design limitations on sag, conductor OD, maximum structure tension load, and vertical weight while allowing continuous operation at 1,350 amps. The following table and graphs summarize the conductors presented during the panel session.

In the case of all ACSR and HTLS conductors, we are concerned with the composite behavior at high temperature. All of the HTLS conductors and the original ACSR conductor behave in a similar fashion at high temperature. In all the designs, the core has a lower thermal elongation rate than the outer layers of aluminum. As the temperature of the conductor increases, the sag also increases as described in the following:

1. At temperatures modestly above everyday levels, the conductors elongate at a rate which is due to the combined thermal elongation of the core and the outer layers of aluminum.
2. At a conductor temperature called the "kneepoint" temperature, the tension in the aluminum layers goes to zero and all the tension is in the core.
3. At temperatures above the kneepoint, the conductor elongates at a rate primarily determined by the core.

The goal of HTLS conductors is to minimize the thermal elongation rates both above and below the kneepoint temperature and to move the kneepoint to as low a temperature as is possible. A plot of Final Sag vs. Temperature for the various HTLS conductors considered in the IEEE Uprating case is shown in Figure 9-3. As shown in the graph, all of the conductors presented in the case study have less sag than the traditional ACSR conductor at elevated temperatures but this result is achieved in different ways.

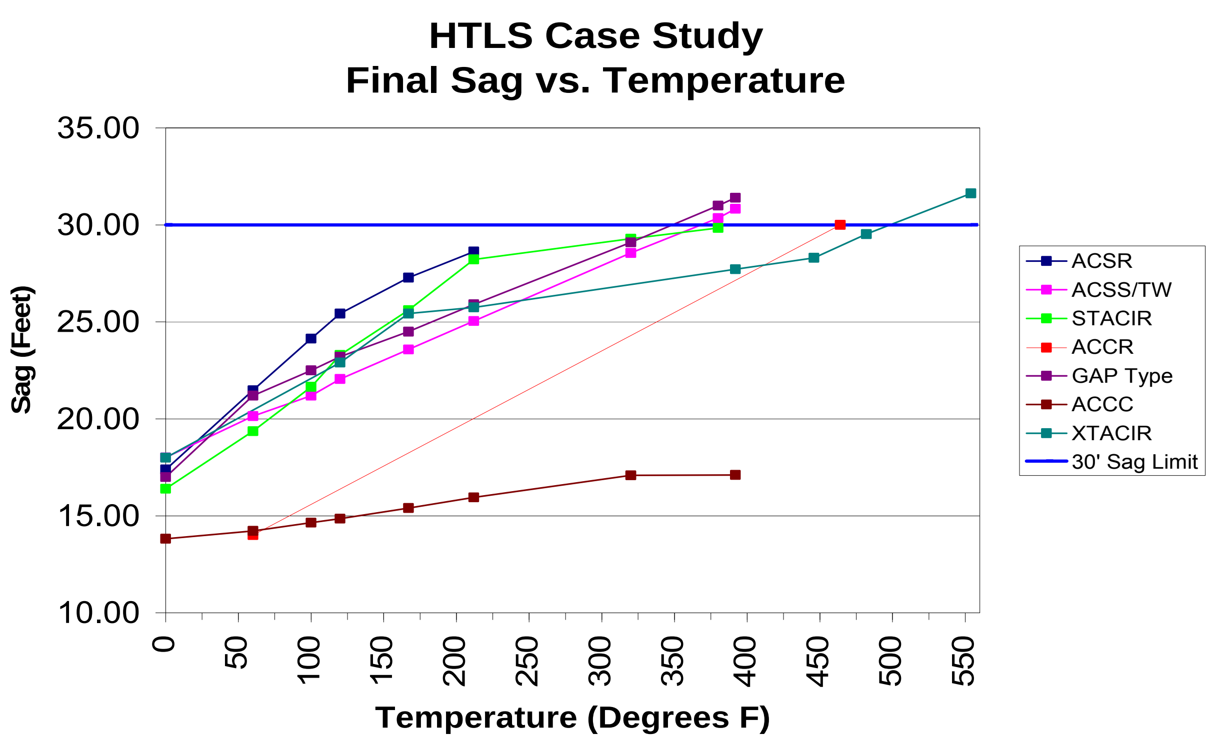


Figure 9-3
Comparison of Sag as a function of Conductor Temperature for IEEE Test Case

In particular, one can see that the kneepoint for the various HTLS conductors occurs at a lower conductor temperature than for ordinary ACSR (normally between 140°F or 60°C and 248°F or 120°C for high and low steel content ACSR, respectively). The annealed aluminum HTLS conductors (ACCC and ACSS) have a kneepoint temperature which is on the order of 60°F or 15°C since the annealed aluminum strands are assumed to have little or no tension under final conditions. The highest HTLS conductor kneepoint temperature occurs for those having an Invar steel core.

One can also see that the thermal elongation over the whole range of interest is much lower for ACCC than for any of the other conductors. Finally, note that both the ACCR and ACCC HTLS conductors are installed with less final everyday sag because of their lower weight per unit length.

Conductor ampacities were plotted below to show the gains in current flow after the HTLS conductors are installed. All of the proposed HTLS conductors exceeded the 1,350 and 1,500A goals while limiting the sag to acceptable levels.

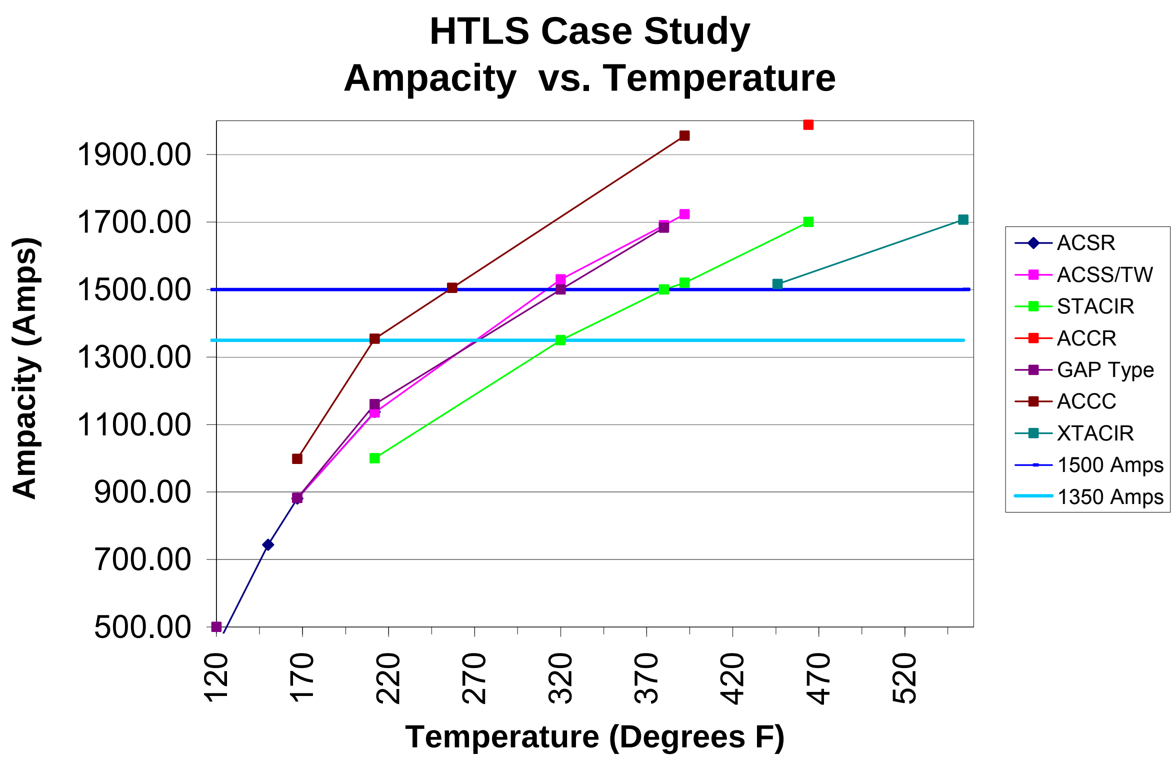


Figure 9-4
Comparison of HTLS Ampacities for IEEE Uprating Test Case

In addition to meeting the limitations on sag at high temperature, the various HTLS reconductoring solutions had to meet the limitation on sag under 1 inch ice loading at 32^{o}F and to avoid pulling the conductor so tight that it developed wind vibration fatigue problems. The ACCC conductor and ACSS with its normal high strength steel core had the most difficulty in meeting these limitations. Both conductors use annealed aluminum strands, which if they are pre-stressed, yield low tension in the aluminum layers and high self-damping.

The ACCC conductor had the largest change in sag due to ice load since the composite core has a modulus which is only about 2/3 that of steel. In areas having severe ice load requirements, reconductoring with the ACCC and ACSS HTLS conductors may be challenging.

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CONCLUSIONS & RECOMMENDATIONS

The advantage of reconductoring existing lines with HTLS conductors is that the thermal rating of the line can be increased substantially with minimal modification to existing transmission line structures. To limit the need for structural modification, these high temperature replacement conductors must operate at much higher temperatures than ordinary bare overhead conductor without exceeding the original maximum sags and without causing a large increase in the original maximum tension and ice or wind structure loads. Increased sag would require raising the existing structures. Increased structure loads would require replacement or reinforcement of dead-end and angle structures and perhaps even tangent structures.

- One of the primary limitations on high temperature operation of ordinary bare stranded aluminum conductors is loss of aluminum tensile strength. Even when the aluminum strands have a substantial steel stranded reinforcing core, continuous operation is typically limited to 100^{o}C or less. HTLS conductors can operate continuously at temperatures between 150^{o}C and 250^{o}C depending on the particular design and wire materials.
- Those HTLS conductors which employ annealed aluminum are observed to have a lower elastic modulus than conventional ACSR. In geographical areas which experience severe ice loadings, this type of HTLS conductor may yield sags under heavy loading conditions which are comparable or even larger than the sag at high temperature.
- If HTLS conductors with annealed aluminum strands are pre-stressed, one may expect their self-damping properties to be very favorable and initial stringing sags may be quite small without causing vibration fatigue.
- Those HTLS conductors which employ high temperature resistant alloys of aluminum (e.g. TAL and ZTAL), have an elastic modulus which is comparable to conventional ACSR of the same stranding. While the sag under heavy loading conditions observed with these HTLS conductors is likely to be less than their high temperature sag, their high elastic modulus is likely to result in relatively high structure loads.
- HTLS conductors with TAL or ZTAL aluminum, are likely to yield self-damping properties which are similar to conventional ACSR.
- Limited corona testing of the various HTLS conductors indicates that these conductors are likely to yield corona noise levels similar to conventional ACSR of the same diameter.
- Each of the HTLS conductors studied appears to have suitable connectors and hardware available. There is no reason to suspect that these conductor systems are unreliable in the short run (up to 5 years).
- The installation of the various HTLS conductors does not appear to be a problem. The most complex conductor system to install is the Gapped HTLS (G(Z)TACSR). The simplest

conductor system is probably the ZTACIR conductor since the aluminum is not subject to damage during stringing and the core is not particularly sensitive to shear forces.

- There does not appear to be a compelling reason to choose one of the HTLS conductors over the others except possibly for cost. All of the HTLS conductors studied have the following characteristics:
  - Has a low thermal elongation rate.
  - Can operate continuously at temperatures well above 100^{o}C without any deterioration of mechanical or electrical properties.
  - Has the same or lower resistance as the original conductor of the same outer diameter.

It is less clear which of the HTLS conductors studied in this project will work best in a particular uprating situation. However, stress-strain models for each of the HTLS conductors are available and utility engineers can evaluate each of the choices in a given uprating problem.

The best conductor choice ultimately depends on the existing clearance buffer, original design margins, environmental loading conditions, and the magnitude of the desired rating increase. The case study shows how HTLS conductors can be successfully used to obtain thermal rating increases of at least 50% and minimizing the need for expensive structure modifications.

11
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