High-Temperature, Low-Sag Transmission Conductors

Technical Report

High-Temperature, Low-Sag Transmission Conductors

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REPORT SUMMARY

An attractive method of increasing transmission line thermal rating (uprating) involves replacing the original (typically) steel-reinforced aluminum conductor (ACSR) with a high-temperature, low-sag (HTLS) conductor with approximately the same diameter as the original conductor. The increase in thermal rating of existing lines reconductored with one of these HTLS conductors varies from 20% to 80% depending on whether the replacement HTLS conductor is able to reach its maximum operating temperature within electrical clearance limits.

Background

The overwhelming majority of overhead transmission lines use ACSR. On a continuous basis, ACSR may be operated at temperatures up to 100^{o}C and, for limited time emergencies, at temperatures as high as 125^{o}C without any significant change in the conductor's physical properties. These temperature limits constrain the thermal rating of a typical 230-kV line to about 400 MVA. Given the many changes in the way the power transmission system is being planned and operated, there is a need to reach higher current densities in existing transmission lines. Replacing original ACSR conductors with HTLS conductors with approximately the same diameter is one method of increasing transmission line thermal rating. HTLS conductors are effective because they are capable of (1) high-temperature, continuous operation above 100^{o}C without loss of tensile strength or permanent sag-increase (so that line current can be increased) and (2) low sag at high temperature (so that ground and underbuild clearances can still be met without raising or rebuilding structures).

Objectives

To describe HTLS conductors in various stages of development and commercialization.

Approach

HTLS conductors considered in the report are

- ACSS and ACSS/TW [Aluminum Conductor Steel Supported] – Annealed aluminum strands over a conventional steel stranded core. Operation to 200^{o}C.
- (Z)TACIR [Zirconium alloy Aluminum Conductor Invar steel Reinforced) – High-temperature aluminum strands over a low-thermal elongation steel core. Operation to 150^{o}C (Tal) and 210^{o}C (ZTAl).
- GTACSR ["Gapped" TAL alloy Aluminum Conductor Steel Reinforced] – High-temperature aluminum, grease-filled gap between core / inner layer. Operates to 150^{o}C.

- ACCR [Aluminum Conductor Composite Reinforced] – High-temperature alloy aluminum over a composite core made from Alumina fibers embedded in a matrix of pure aluminum. Operation to 210^{o}C.
- CRAC [Composite Reinforced Aluminum Conductor] – Annealed aluminum over fiberglass/thermoplastic composite segmented core. Probable operation to 150^{o}C.
- ACCFR [Aluminum Conductor Composite Carbon Fiber Reinforced]– Annealed- or high-temperature aluminum alloy over a core of strands with carbon fiber material in a matrix of aluminum. Probable operation to 210^{o}C.

Results

The HTLS conductors described in this report are at various points in this development process:

- ACSS is commercially available and needs little additional research or development. The manufacturer has performed all necessary laboratory tests to allow sag-tension calculations and it has been used extensively in line upgrading at many utilities.
- The Japanese developers of high-temperature alloy conductors with Invar steel cores (ZTACIR and TACIR) and the gapped conductor (GTACSR) have performed many laboratory tests, and stress-strain and creep data is available for sag-tension calculations. These conductors have not been used, however, in actual U.S. installations. Field testing might be useful to members in accelerating their acceptance or rejection.
- The 3M conductor, ACCR, has been laboratory tested as part of its development process, but it has only been field tested in a single span at Xcel Energy. Field tests would be useful in identifying this conductor's strengths and weaknesses.
- CRAC and ACCFR are composed of materials (fiberglass and carbon fiber composite) that have not been defined or laboratory tested. Research on these conductors should define material properties, including conductivity, tensile, and creep elongation properties at high temperature, and corrosion resistance. Until properties of the reinforcing materials are well-defined, there is no need for nor is it possible to execute field tests.

EPRI Perspective

HTLS conductors discussed in this report are in various stages of research or commercial development. The document is not an attempt to find a "best" conductor for all high-temperature applications. There is not enough data on some conductors to make this decision. This is simply a review of the known HTLS conductor traits, an assessment of their commercial state, and a limited comparison of their effectiveness as replacement conductors in existing lines. The report can serve as the basis for field test planning and for evaluating the need for laboratory testing.

Keywords

High temperature conductors   Transmission line sag   Thermal ratings

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1 INTRODUCTION

Most existing overhead transmission lines use steel reinforced aluminum conductors (ACSR). On a continuous basis, ACSR may be operated at temperatures up to 100^{o}C and, for limited time emergencies, at temperatures as high as 125^{o}C without any significant change in the conductor's physical properties. These temperature limits constrain the maximum current density of ACSR to the range of 1 to 2 amps/kcmil (2 to 4 amps/mm^2). This in turn limits the thermal rating of a typical 230 kv line with a single 795 kcmil ACSR conductor per phase to about 400 MVA.

In order to increase the thermal rating of existing lines, one method involves replacing its ACSR conductors with special "high-temperature low-sag" (HTLS) conductors having approximately the same diameter as the original ACSR but being capable of operation at temperatures as high as 200^{o}C with less thermal elongation than ACSR. Ideally, these special HTLS conductors can be installed and operated without the need for extensive modification of the existing structures and foundations.

As with ACSR, HTLS conductors typically consist of aluminum wires helically stranded over a reinforcing core. Most of the electrical current flows in the high conductivity, low density, aluminum strand layers. Most of the tension load is in the reinforcing core at high temperature and under high loads. The comparative performance of the HTLS conductors depends on the degree to which the aluminum strand and reinforcing core's physical properties are stable at high temperature and on the elastic, plastic, and thermal elongation of the combined HTLS conductor.

The HTLS conductors discussed in this report are in various stages of research or commercial development. The document is not an attempt to find a "best" conductor for all high temperature applications. There is not enough information on some conductors to make this decision. This is simply a review of the known HTLS conductor characteristics, an assessment of their commercial state, and a limited comparison of their effectiveness as replacement conductors in existing lines.

The report can serve as the basis for field test planning and for evaluating the need for laboratory testing.

2
DESIGN CONSTRAINTS ON RECONDUCTORING EXISTING LINES

Electrical, mechanical and thermal constraints on replacement conductors are considerably more restrictive than those for conductor used in new lines. Trade-offs between conductor resistance, thermal elongation, mechanical strength, and high temperature stability of such properties will be described. An understanding of such trade-offs can serve as the basis for field-testing.

The restrictions on reconductoring include the following:

- Transverse structure load and tension limits are set. Any change requires structure reinforcement.
- Attachment height and span lengths are fixed unless structures are raised or moved.
- Mid-span spacing of phases is fixed.
- The type of insulators ("I", "V", "horizontal V", or "post") is usually difficult to change.

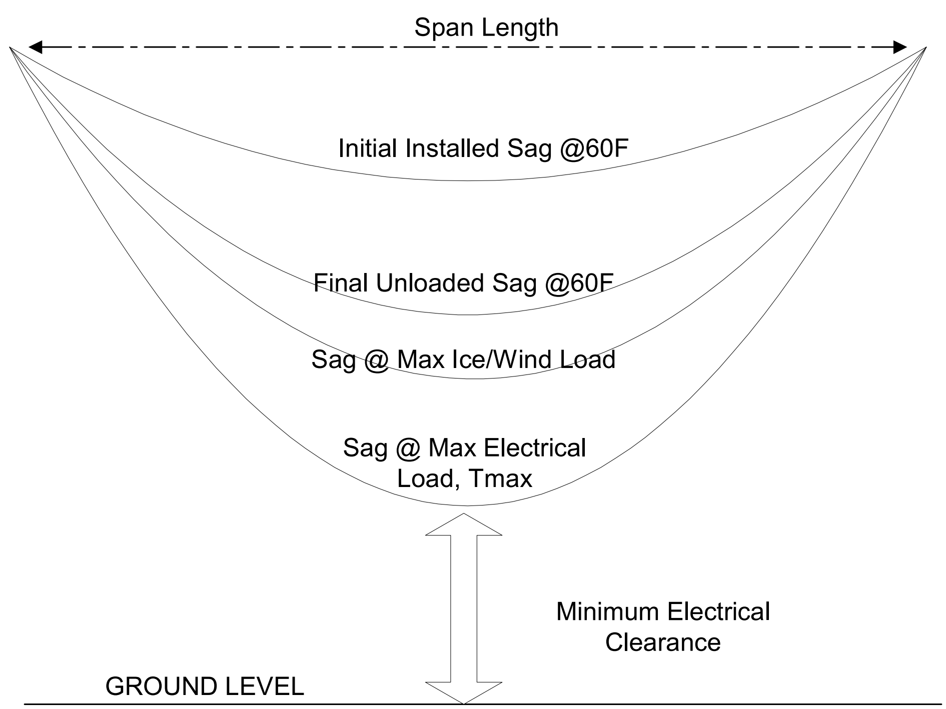

Figure 2-1
Sag Diagram

In order to increase the ampacity of an existing line by reconductoring, either resistance of the conductor must be decreased or the new conductor must operate at a higher temperature than the old:

- The resistance of the phase conductors can be reduced if the existing conductor is replaced with a larger conductor (i.e. greater crossectional area) and/or with a conductor having higher effective conductivity (e.g. use Alumoweld in place of galvanized steel core wires).
- In order to operate the new conductor at a high maximum allowable temperature, some way has to be found to limit the maximum sag at high temperature to that of the existing line (refer to Figure 2-1).

Sag Constraints

As shown in Figure 2-1, the original conductor was installed at the "Initial installed sag" using stringing charts. Over time, the initial unloaded sag will increase to a final "everyday" sag condition (typically at 60^{o}F with no ice and wind). The difference in sag between initial and final sag is the result of both occasional wind/ice loading events and the normal creep elongation process of tensioned aluminum strands over time. Under final conditions, the sag may increase further due to ice/wind loading or high electrical loads. For most transmission lines, the larger reversible increase in final sag occurs as a result of electrical rather than mechanical loads as is shown in Figure 2-1. The temperature corresponding to the maximum electrical load is called the maximum allowable conductor temperature or the line design temperature. Values of between 49^{o}C and 125^{o}C are common. For transmission conductors with no steel core, the maximum allowable conductor temperature may be reduced in order to limit annealing of aluminum.

When reconductoring, the new conductor must be installed, such that over time, the final unloaded sag at the new maximum allowable conductor temperature does not exceed the original conductor's final sag at the original maximum temperature.

Tension Constraints

The other important constraint on reconductoring is typically that the new conductors must not exceed the original load limits of the existing structures. For tangent structures, the governing transverse loads are primarily a function of the conductor diameter. Thus the replacement conductor diameter must be within about 10% of the existing conductor unless the tangent structures are to be reinforced. For angle and dead-end structures, the governing loads are primarily a function of the initial maximum conductor tension. Unless these structures are to be reinforced or replaced, the replacement conductor's maximum tension should not exceed the initial maximum conductor tension used in the structure design.

3
WIRE MATERIAL PROPERTIES

Transmission conductors are constructed from helically stranded combinations of individual wires. Certain wires are primarily used for mechanical reinforcement (e.g. galvanized steel), others solely to conduct electricity (e.g. annealed aluminum or copper), and many both for their mechanical and electrical properties (e.g. "Hard-drawn aluminum or copper). In the most common type of transmission conductor, ACSR, the steel and the aluminum strands are important mechanically. With 26/7 Drake ACSR, the total tensile strength of 31,500 lbs is the sum of 13,500 lbs in the aluminum and 18,000 lbs in the steel core.

Examples of attractive material wire properties are:

- High conductivity
- High ratio of tensile strength to weight
- Retention of tensile strength at high temperature
- Low plastic elongation
- High mechanical self-damping
- Low ratio of outside diameter to crossectional area
- Easy fabrication into wire
- Weatherability (unaffected by humidity, sun, rain)

It is reasonable to assume that any HTLS conductor will consist of helically stranded wires and that it is likely to have a mechanical reinforcing core surrounded by multiple helical layers of conducting wires. Table 1 lists material properties for the various component wires used or proposed for use in HTLS conductor.

Note that normal ACSR consists of 1350-H19 aluminum wires [4], helically stranded around a core of high strength (HS) steel core wires. 1350-H19 aluminum is nearly pure aluminum that is limited to continuous operation below 100C. Above 100^{o}C, 1350-H19 aluminum wires lose tensile strength over time and, after extended exposure to high temperature, 1350-H19 becomes "fully annealed" wire (designated 1350-H0). 1350-H0 is chemically identical to 1350-H19 but all "work-hardening" of the wires inherent in drawing the wires from rod has been removed.

1350-H0 has a tensile strength less than half that of 1350-H19 and breaks at an elongation of 10% to 20% instead of 1%. It is unaffected by further exposure to high temperatures. Annealed aluminum wires are attractive for use in HTLS conductor meet the criteriait has a greatly reduced tensile strength and can be operated to 350C without any change in its properties.

TAL and ZTAL [12] are Zirconium aluminum alloys that can be operated at temperatures of up to 150^{o}C and 210^{o}C, respectively, without loss of tensile strength.

Aweld is Alumoweld which is HS steel wire with a thick cladding (10% of diameter) of aluminum that increases the wire conductivity and improves corrosion resistance in ACSR.

HS steel and EHS steel wires are typically supplied galvanized for corrosion resistance. Ordinary galvanizing limits the continuous operation of steel core wires to about 200C. High quality "Galfan" [11] coated steel wires are capable of operation to 350C.

Invar steel alloy wires [13] have a reduced rate of thermal elongation and a slightly lower tensile strength than HS steel wires. At high temperature, the sag of invar reinforced aluminum conductor increases less than ACSR with temperature.

3M's Alumina Composite wires [15] are quite different from steel but serve the same purpose of providing mechanical strength and low thermal elongation. This composite material has the highest conductivity and the lowest thermal elongation of the commercially available reinforcing wires.

Table 3-1
Wire Material Properties

Material	Maximum Continuous Temp [deg C]	Max Elongation [%]	Modulus/Tensile Strength [Mpsi / Kpsi]	CTE [10^{-6} per °C]	Density [g/cc]	Conductivity [%IACS]
Commercially Available Conducting Wire Materials						
1350-H19	100	1	7/24	23	2.703	62
1350-H0	250	20	7/10	23	2.703	63
TAL	150	1	7/24	23		60
ZTAL	210	1	7/24	23		60
Commercially Available Reinforcing Wire Materials						
Aweld	250	3	23/1		6.59	20
HS Steel	200 to 350	3	28/180	11.5	7.78	8
EHS Steel		3	28/210	11.5	7.78	8
INVAR		3	22/160	6.6	7.78	15
3M Alumina Composite	250	0.7	28/200	6.3		30
Experimental Reinforcing Wire Materials						
Thermoplastic Composite	<150	3	7/200	~ 6	1.5	0
Graphite fibers*	250	~ 1	33/360	~ -1.	1.8	0

* Graphite fibers would almost certainly be embedded in a matrix that will reduce the modulus and tensile strength shown by as much as 50%.

The exact material properties of fiberglass and graphite composite are very uncertain as these materials are presently under development.

The development of a fiberglass composite for conductor reinforcement is not complete and the effect of high temperature exposure is uncertain [16]. The mechanical and electrical parameters listed for information and are subject to change as the materials are modified in the future. The advantage of fiberglass is its low weight and low thermal elongation. Its elastic modulus, however, is only about 25% that of the other reinforcing materials being approximately the same as aluminum. It seems unlikely that a fiberglass-reinforced conductor would be suitable for use in high ice and wind load areas.

The values shown in Table 3-1 for modulus and tensile strength of the graphite fiber is for the strand material alone. Since the strands must almost certainly be embedded in an aluminum matrix of some sort, the modulus and the tensile strength will be considerably less than the values shown for the fiber alone. The advantage of the carbon composite reinforcing material is low weight and negative thermal elongation, however, carbon fibers react chemically with aluminum.

4

HIGH TEMPERATURE-LOW SAG CONDUCTOR CHOICES

This evaluation report includes conductors that are at various stages of this normal development process. The study is too brief to provide detailed comparisons of high temperature low sag (HTLS) conductors under the many design conditions that can be encountered. In addition there are uncertainties concerning some handling and long term sag-tension-temperature behavior that can only be determined by experiment. The report does provide a description of each the mechanical and electrical characteristics of each conductor type, an evaluation of how "commercial" the conductor is at present, and some typical performance comparisons.

The HTLS conductors considered in the report are:

1. ACSS [10] and ACSS/TW [11] Commercially available HTLS conductors that can be readily purchased and installed with an extensive history of utility experience. There are multiple suppliers within the US. Initial concerns about installation and surface roughness problems due to the use of annealed aluminum strands have been overcome and the cost premium is minimal. The main limitation with ACSS is its relatively low strength and modulus that limit its use in regions experiencing high ice loads.

2. ZTACIR [12] Commercially available through importation from Japan. While there is little or no field experience with this conductor in the US, there is extensive laboratory test data on both the Invar steel core and the Zirconium aluminum alloy wire material. It is not clear whether multiple suppliers will develop in the US. There appear to be no special problems with installation and termination of ZTACIR. Invar steel is somewhat weaker than conventional steel core wire limiting its use in high ice load areas and compression effects in the aluminum strands make its thermal elongation rate at high temperature uncertain.

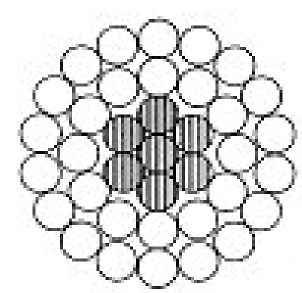

Figure 4-1
ZTACIR

3. GTACSR [14] Commercially available through importation from Japan. Limited field experience from National Grid installation in England (A 2 km length of GTACSR was successfully installed by National Grid). Extensive laboratory test data and detailed installation instructions are available. 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 fitting required for long lines.

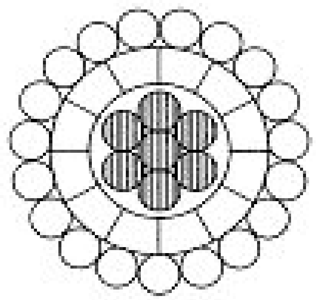

Figure 4-2
GTACSR

4. ACCR [15] Commercially available in limited quantities from the 3M Company. Reasonably extensive tests have been performed on several sizes of this conductor under laboratory conditions and terminations and suspension clamps are available from Preformed Line Products. Xcel Energy successfully completed a field test, with a single 800 ft span, in Minneapolis. The installation of this conductor appears to be reasonably straightforward but may require special large blocks and careful handling.

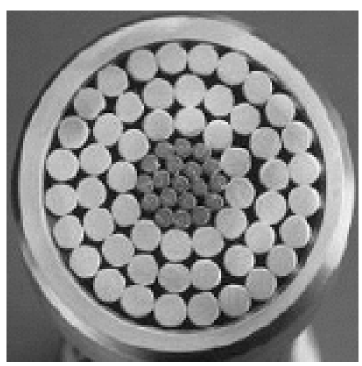

Figure 4-3
ACCR

5. CRAC [16] Not commercially available from any of the major manufacturers nor from the inventor Goldsworthy Company. A Mr. C.W.Arrington of Transmission Technology Corp. claims to be able to supply the conductor in reel lengths. Laboratory tests have been limited to tests on short samples of fiberglass core. The use of annealed trapezoidal wire aluminum strands in combination with a low modulus fiberglass core makes its use in high ice load areas unlikely. A splice has been proposed but not demonstrated.

6. ACCFR [17] Carbon fiber reinforced aluminum conductor is not commercially available. The carbon fiber core has been produced in a variety of forms but only in short lengths. The negative thermal elongation behavior of carbon fibers combined with low density and "steel-like" tensile strength and modulus make this conductor potentially attractive. The low shear strength of carbon fibers, the problems of corrosion, and high fabrication and material cost are possible drawbacks.

5
TERMINATIONS, SPLICES, HARDWARE, AND INSTALLATION ISSUES

Terminations, splices, hardware, and installation procedures for standard ACSR and AAC bare overhead conductors are well understood and problems are relatively rare when manufacturer's installation instructions are followed. The introduction of new types of conductor may require modifications of existing equipment designs and procedures. It seems likely that problems and uncertainties involving tension stringing, termination, splicing, and support of new types of HTLS replacement conductors will be a primary focus of subsequent field-tests.

Some examples of installation procedures that are peculiar to certain HTLS conductors include the following photograph [14](Figure 5-1), that shows the special termination procedure for the GTACSR conductor installed at National Grid.Here the aluminum strands are shown as the crew is separating them in order to grip the steel core.

Figure 5-1
Termination of GTACSR Conductor at National Grid [14]

Tension stringing concerns include the transfer of tension load from a grip to the reinforcing core, the minimum size stringing block, and short term creep elongation that may impact sagging.

With the proposed CRAC conductor, the use of a segmented fiberglass/thermoplastic core requires a special splicing technique. The proposed splice is shown in the following picture [16]. The CRAC designs include considerations for splicing, because without it the designs cannot be implemented by the utilities due to a lack of practicality. Figure 5-2 shows the splicing concept for CRAC-121.

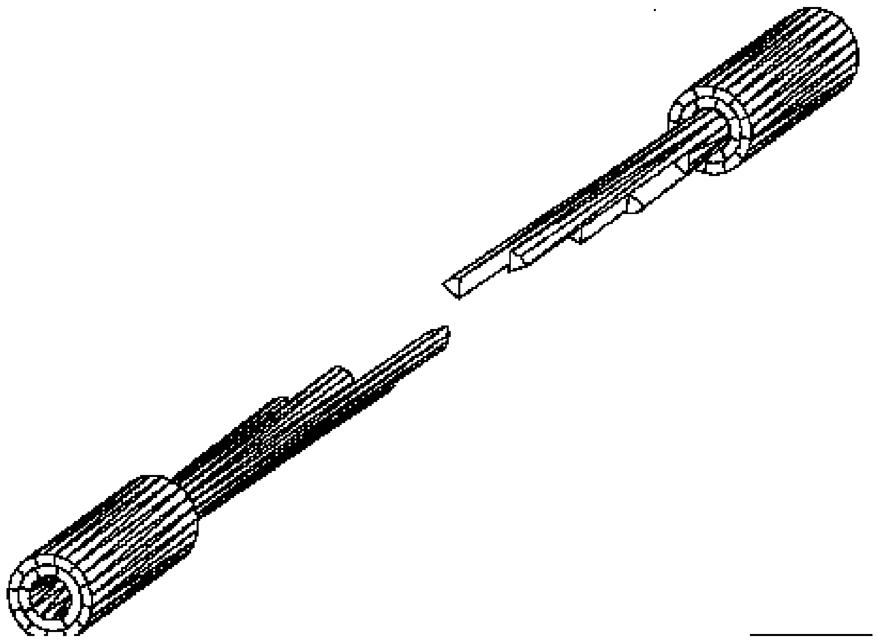

Figure 5-2
Proposed Splice Method for Fiberglass Core of CRAC Conductor[16]

By staggering the bond lines between segments in the lengthwise direction there is a gradual transfer of load. This type of joining is regarded in the aerospace industry as the strongest bonded connection that can possibly be made. This proposed splice is not commercially available.

In contrast to some of the other HTLS conductors, the splicing, installation, and termination of ACSS is well understood. ACSS requires special two-sleeve splices [9] 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. One point of uncertainty, however, involves the ability of conventional suspension clamps to operate at temperatures of 200°C or more.

Terminations and suspension hardware for the ACCR conductor have been developed and tested. A dead-end for ACCR used in the initial field test at Xcel Energy is shown in Figure 5-3. Armor Grip suspension clamps are recommended for suspension hardware. 3M Company has performed extensive hardware tests in cooperation with EDF and Preformed Line Products.

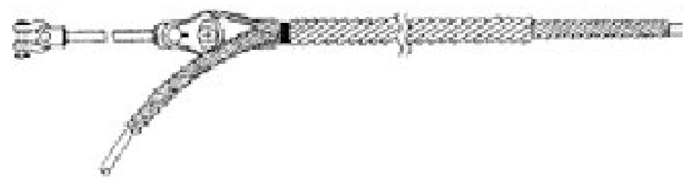

Figure 5-3
Termination for ACCR HTLS Conductor

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 manufacturer provides installation recommendations and arranges that connectors, support clamps, and terminations work well at the extreme temperatures that are likely to be encountered in HTLS conductor applications.

6
CONDUCTOR DEVELOPMENT PROCESS

Overhead transmission lines must be very conservatively designed and built such that the public is not injured by contact with their energized conductors. To assure the public safety, any new conductor must go through a very rigorous series of tests to prove that the conductor will not break nor sag into contact with people, vehicles and other conductors. While no federal or state law specifies this process, power utility line design engineers normally require the following laboratory tests and technical data prior to the onset of field-testing:

- Stress-strain tests showing initial and final curves
- Creep elongation data showing permanent elongation as a function of time for various tension levels
- Conductor weight per unit length
- Conductor tensile strength
- Resistance per unit length

In addition to knowing these conductor parameters, it is normally necessary that methods of terminating, splicing and supporting the conductor are specified and techniques for tension stringing demonstrated. These field tests would typically include documentation of the tension stringing, sagging and clipping processes followed by a period of time during which the conductor would be monitored while carrying full line voltage and typical line current.

Following a successful field test, the manufacturer is normally required to provide a manufacturing specification that includes wire tensile strength, elongation tests, and dimensional checks on component wires, for review by the transmission line owner. The varying stages of development for HTLS conductors is illustrated in Table 6-1.

Table 6-1
Product Development Status for HTLS Conductors

HTLS Conductor	Proof of Concept Tests	Detailed Test & Fitting Data	Field Tests	Manufacturing Specification
ACSS	Yes	Yes	Yes	ASTM
ACSS/TW	Yes	Yes	Yes	ASTM
TACIR	Yes	Yes	[1]	[2]
GTACSR	Yes	Yes	[3]	[2]
ACCR(3M)	Yes	Yes	[4]	
CRAC(CEC)	Yes			

[1] No field test in the US
[2] Japanese manufacturing standards exist
[3] Field Test at National Grid
[4] Single span field test at Xcel Energy

7
HTLS CONDUCTOR COMPARISONS

There are many ways to evaluate the choice of replacement conductor for an existing line. In this section of the report, economic factors, practical installation procedures, inventory control, thermal rating calculations, and continuous versus contingency applications will be discussed.

It seems very unlikely that it will be possible to suggest a single common evaluation method but this discussion will include a description of the most important issues to be considered in such a comparison.

Electrical Losses

The purpose of any power transmission line is to carry electrical power. The energized conductors of the line must carry electrical current without excessive losses. Electrical losses over a given transmission path at a given level of electrical current are a function of the conductor resistance, the length of the path, and time. For a typical balanced 3-phase line, the losses in each of the phase conductors is the same.

Electrical conductor losses determine the cost of power losses per unit length for an overhead line and also the conductor temperature attained as the result of high current levels. Power flow is seldom limited because of power losses but is commonly limited to avoid excessively high temperatures.

Resistance Per Unit Length

The resistance of a stranded bare overhead conductor is equal to the product of metal resistivity and crossectional area of the strands adjusted for frequency, temperature, and ferromagnetic losses if any.

For conductors with ferromagnetic reinforcing core wires, the 60 Hz resistance may be up to 5% higher than for those with non-ferromagnetic core wires due to magnetic losses at high current levels.

Basis for Resistance Comparison

The conductivity of "electrical conductor" grade 1350-H19 aluminum is 62% of the International Annealed Copper Standard (IACS). If it is annealed, the conductivity may increase slightly to 63%. With the addition of alloying compounds, the conductivity is usually less than 62%.

Galvanized steel wires have a conductivity of 8%IACS, Alumoweld wires 20% IACS, and the 3M composite core wires, 30% IACS.

Generally, comparisons of conductor resistance should be made on the basis of equal crossectional area. Conductors with round wires should not be compared to conductors with trapezoidal wires having the same diameter.

Sag Increase With Conductor Temperature

Overhead transmission lines must maintain certain minimum distances to ground under all operating conditions (both high current/temperature and high ice and wind loads). This is essential to the public safety.

In most cases, sag under ice and wind loading is less than the sag that occurs for high currents. Therefore, in order to maintain adequate clearance to ground and to other conductors, a maximum power flow on transmission lines (the thermal limit) is specified and the transmission operator monitors the power flow on each line such that the thermal rating is not exceeded.

When reconductoring an existing transmission line, the replacement conductor should be capable of carrying more electrical current with the same maximum sag as the original conductor. To accomplish this, the replacement conductor should have the following characteristics:

- Low thermal elongation
- Low initial sag
- Low plastic elongation

Conventional ACSR conductors are typically installed to sags on the order of 2% of span length. Thus a 1000 ft span of Drake ACSR may be installed to an initial sag of 20ft. As a result of exposure to ice and wind loads and time, the initial sag may increase by about 15% to about 23 ft and during high current events that raise the conductor temperature to 75C, to 30 ft.

A desirable replacement conductor might be installed at 20 ft or less of sag, exhibit no plastic elongation (final sag = initial sag), elongate thermally at half the rate of DRAKE ACSR such that the 30 ft maximum sag is not reached until the conductor temperature is much higher than 75C, and with tension under maximum wind and ice loading no higher than the original design.

Basis for Sag Comparison

The various conductor characteristics that control maximum sag must be taken together. That is, a replacement conductor that does not elongate thermally is useless if it breaks under ice and wind load. On the other hand, a conductor that elongates somewhat more than the original conductor under ice and wind load may be desirable if it keeps the maximum structure tension loads down.

Comparisons of sag-tension behavior must be done with a computer program such as Alcoa's SAG10. A replacement conductor that has attractive characteristics in one design situation may be less desirable in another case. To perform these kinds of calculations, the conductor manufacturer must supply adequately detailed conductor stress-strain data, creep data and thermal elongation information.

Without such detailed data it is possible to do only rough comparisons. Clearly, low thermal elongation is desirable in any replacement conductor as is adequately low elastic and plastic elongation under high loads.

High Temperature Sag Uncertainties

Until just recently, transmission lines were seldom run to temperatures in excess of 100C. In fact until the early 1970's it was common to design transmission lines for a maximum conductor temperature of 120F (49C). Even when lines are reconductored with special high temperature conductor capable of operation up to 200C, power system conditions rarely cause such extreme temperatures to occur. As a result there is little field data to verify the calculated sag variation of conventional ACSR with temperatures above 75C.

The primary uncertainty about ACSR at high temperature involves the thermal elongation at temperatures above the "kneepoint" of the conductor. The kneepoint temperature is typically a function of the steel content:

Table 7-1
"Kneepoint" Temperature for ACSR Conductors as a Function of Steel Content

ACSR Stranding	Type Number	Kneepoint temperature [C][1]
42/7	5	190
45/7	7	150
54/7	13	95
26/7	16	70
30/19,30/7	23	35

[1] Temperatures beyond which all conductor tension is transferred to the steel core

At temperatures up to the "kneepoint", where the aluminum and steel core are both in tension, the thermal elongation of ACSR is given by Eq. 7-1and Eq. 7-2.

$$\alpha_{AS} = \alpha_{AL} \cdot \left(\frac{E_{AL}}{E_{AS}}\right) \cdot \left(\frac{A_{AL}}{A_{TOTAL}}\right) + \alpha_{ST} \cdot \left(\frac{E_{ST}}{E_{AS}}\right) \cdot \left(\frac{A_{ST}}{A_{TOTAL}}\right) \qquad \textbf{Eq. 7-1}$$

$$E_{AS} = E_{AL} \cdot \left(\frac{A_{AL}}{A_{TOTAL}} \right) + E_{ST} \cdot \left(\frac{A_{ST}}{A_{TOTAL}} \right) \qquad \textbf{Eq. 7-2}$$

where

E_{AL} = modulus of elasticity of aluminium (GPa)

E_{ST} = modulus of elasticity of steel (GPa)

E_{AS} = modulus of elasticity of aluminium-steel composite (GPa)

A_{AL} = area of aluminium strands, mm^2

A_{ST} = area of steel strands, mm^2

A_{TOTAL} = total cross-sectional area, square units, mm^2

α_{AL} = aluminium coefficient of linear thermal expansion, per ^oC

α_{ST} = steel coefficient of thermal elongation, per ^oC

α_{AS} = composite aluminium-steel coefficient of thermal elongation, per ^oC

Using elastic moduli of 55 and 190 GPa for aluminium and steel, respectively, the elastic modulus for the 500-A1/S1A conductor is:

$$E_{AS} = (55) \times \left(\frac{500}{565} \right) + (190) \times \left(\frac{65}{565} \right) = 70.5 GPa \qquad \textbf{Eq. 7-3}$$

and the coefficient of linear thermal expansion is:

$$a_{AS} = 23 \times 10^{-6} \times \left(\frac{55}{70.5} \right) \times \left(\frac{500}{565} \right) + 11.5 \times 10^{-6} \times \left(\frac{190}{70.5} \right) \times \left(\frac{65}{565} \right) = 19.5 \times 10^{-6} \, / \, ^\circ C \qquad \textbf{Eq. 7-4}$$

At temperatures above the “knee point” temperature, there is a good deal of uncertainty about thermal elongation. Up until the last 5 to 10 years, calculation methods such as SAG10 [20] assumed that the conductor’s thermal elongation rate was that of steel at temperatures above the knee point. In a number of indoor and outdoor experiments with ACSR, it appears that the thermal elongation rate above the knee point is greater than that of steel alone.

The two main theories concerning this behavior are those of Rawlins [22] and Barrett [23]. There are a number of experiments that confirm that the thermal elongation rate is greater than that of steel alone. Barrett’s theory involves the natural ability of aluminum helically wound strands to support limited compression. Rawlin's theory centers on residual stresses in the aluminum strands that are caused during manufacture. In both cases, the compression stress does not exceed 1500 to 2500 psi (10 to 20 Mpa).

The applicability of these theories to HTLS conductors is uncertain but important to their evaluation. There is uncertainty even with ACSR. There is more uncertainty with other high temperature aluminum alloys and reinforcing materials intended to replace high strength galvanized steel. It appears that the collection and analysis of sag-temperature-tension field data for field installations with high current loading is essential to evaluating HTLS conductors.

3M has performed outdoor tests on the sag behavior of ACCR in cooperation with EDF. In these tests, a 0.65 inch diameter, 26/7 ACCR two-layer conductor was placed in an 750 ft span and subjected to high current levels that drove the conductor temperature above 200°C. The conductor was installed to an initial tension of 20% of its rated strength at 15C. Experimental points are shown by the symbols and calculated sag by the lines. Note the slope change ("kneepoint") at about 120°C.

In this experiment, the impact of aluminum compression appears to be minimal.

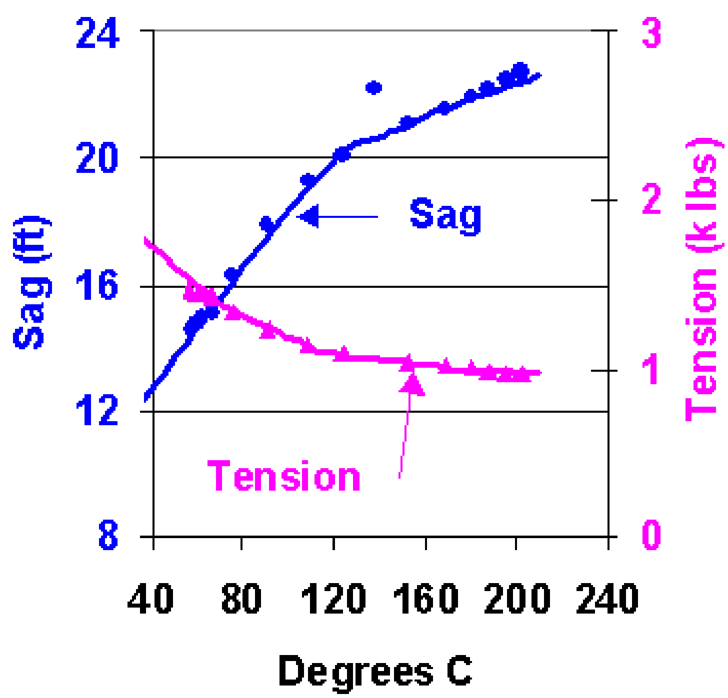

Figure 7-1
Sag Versus Conductor Temperature with 26/7 ACCR Conductor in a Single Dead-End Span

"Elastic Modulus" (Tension Change With Conductor Weight)

Conductor weight per unit length increases when wind blows across or ice forms on transmission line conductors. Table 7-2 shows various ice and wind loading conditions from the National Electric Safety Code for transmission lines. HTLS conductors used for reconductoring existing lines must be able to sustain the increases in conductor weight per unit length that result from such ice and wind loads without violating electrical clearances through excessive sag.

Table 7-2
Transmission Line Loading Districts According to the National Electric Safety Code

Loading Districts				
	Heavy	**Medium**	**Light**	**Extreme Wind Loading**
Radial thickness of ice(in)	0.5	0.25	0	0
Radial thickness of ice(mm)	12.5	6.25	0	0
Horizontal wind pressure(lb/ft^2)	4	4	9	See Figure3-6
Horizontal wind pressure(Pa)	190	190	430	See Figure3-6
Temperature(°F)	0	+15	+30	+60
Temperature(°C)	-18	-10	-1	+15
Constant to be added to the resultant (all conductors) (Lb/ft)	0.30	0.20	0.05	0.0
Constant to be added to the resultant (all conductors) (N/m)	4.40	2.50	0.70	0.0

In addition, since maximum tension loads on dead-end and angle structures are a function of the conductor modulus, excessively strong HTLS replacement conductors can lead to the need for structure reinforcement.

In almost all existing transmission lines using ACSR or even AAC conductors, the sag under maximum electrical load is greater than the sag under maximum ice and wind load. In using HTLS conductors (which are intended to minimize sag at high temperature) the elastic modulus of the conductor can be important.

Replacement Conductor Modulus

The 1350-H19 aluminum wires used in most existing transmission lines have an "elastic" modulus of about 10 Mpsi and, when helically stranded, a modulus of about 8 Mpsi. Similarly, individual high strength steel core wires have an elastic modulus of nearly 30 Mpsi and approximately 26 Mpsi when stranded. The composite modulus of the ACSR conductor is between 8 and 26 Mpsi depending on the ratio of steel core to aluminum area (Type number). The modulus of an HTLS replacement conductor need not be equal to the original conductor but must be adequate to avoid excessive sag under ice and wind load.

Consider, for example, 26/7 ACSR Drake conductor (elastic modulus of about 10.5 Mpsi) installed to an initial 60F unloaded sag of 21.7 ft in a 1000 ft span. When this conductor is under NESC heavy load conditions (0.5 inch ice, 9 psf wind, OF) the sag increases by about 2 ft. When it is heated to 212F, the sag increases by about 10 ft. Clearance to ground is a minimum under high temperature.

Now consider the replacement of the Drake conductor were replaced by a CRAC HTLS conductor (consisting of annealed aluminum strands and a fiberglass core), where the fiberglass core has the same area as the steel core of Drake. Using the approximate modulus shown in Table 7-2 for fiberglass (i.e. 7Mpsi), then the elastic modulus of the CRAC conductor would be about 1 Mpsi. Under NESC heavy loading, the initial sag of 21.7 ft would increase to more than 30 ft but because of the low thermal expansion coefficient of fiberglass the sag at 212F only increases to about 23 ft. Here the use of CRAC HTLS conductor would result in a clearance failure regardless of the reduced high temperature sag.

Rated Strength of HTLS Replacement Conductors

The breaking strength of transmission conductors is an essential parameter in the design of lines and structures. The breaking strength must remain at or above its "rated" value throughout the life of the transmission line. If the breaking strength decreases due to annealing, corrosion, or fatigue, then the line may fail and violate the public safety.

For homogeneous conductors, the breaking strength of the conductor is normally taken as the sum of the minimum average tensile strength of its strands derated by about 5% to account for stranding.

Note that, for a non-homogeneous conductor, the conductor breaks at the minimum elongation for which either component breaks and the composite conductor's breaking strength equals the sum of the tensile loads at which the weaker component breaks.

For example, consider conventional ACSR. The 1350-H19 aluminum strands break at an elongation of approximately 1% whereas the steel core breaks at an elongation of approximately 3%. The conductor's breaking strength is therefore determined using the tensile strength of the aluminum strands (about 24,000 psi) and the tensile stress in steel with a 1% elongation (about 180,000 psi).

In contrast, the rated breaking strength of ACSS with annealed aluminum strands is calculated using the tensile strength of the steel core (about 210,000 psi) and the stress of annealed aluminum strands (about 8,500 psi) at 3% elongation.

Other non-homogeneous HTLS conductors must be evaluated in the same fashion.

The rated strength of HTLS replacement conductors does not necessarily need to be higher than the original. It cannot, however, be dramatically less or the tensile safety factors used in the design will be inadequate.

When materials other than steel are used to reinforce aluminum conductors, several observations apply:

- The physical properties of the reinforcing materials must remain stable at high temperatures.
- The reinforcing material must not react chemically with the conducting strands.
- Regardless of the reinforcing material chosen, if full hard 1350-H19 aluminum strands are used in the replacement conductor, the composite strength will decline at temperatures above 100C.
- If 1350-H0 annealed aluminum strands are used with the reinforcing core, then the rated strength of the composite conductor is essentially determined by the reinforcing core.
- If high temperature alloys of aluminum are used, then the rated strength of the HTLS replacement conductor will determined by the tensile strength of the stranded component with the smallest maximum elongation plus the stress of the other component at that elongation.

8
SAG COMPARISON FOR HTSL CONDUCTORS

One of the possible performance comparisons for HTLS conductors is sag increase with temperature. In this case, it is assumed that the original ACSR conductor is 795 kcmil 26/7 Drake ACSR installed in a 1000ft ruling span to an initial unloaded tension equal to 20% of its rated breaking strength at 60°F. The initial sag of 21.8 ft increases to 25.7 ft due to an ice load event where the conductor was covered with 1.0 inch of radial ice for several hours. The corresponding maximum tension is 15,300 lbs.

Assume that the line was designed to provide minimum clearance to ground for the ACSR Drake at 100°C (212°F). The final sag of Drake at 100°C is 31.7 ft without aluminum compression. 31.7 ft is therefore the maximum allowable sag for any of the replacement conductors. The thermal rating of DRAKE at 100°C is 990 amperes for 2 ft/sec crosswind, 40°C air temperature, and solar heating for Summer at noon.

The replacement conductors considered in the following sag calculations are ACSS, ACSS/TW, ACCR(3M), GTACSR, and TACIR. re-phrase I could not include CRAC conductor because of a lack of test data on thermal elongation and modulus. For each replacement conductor I have assumed equal final unloaded sag at 60°F.

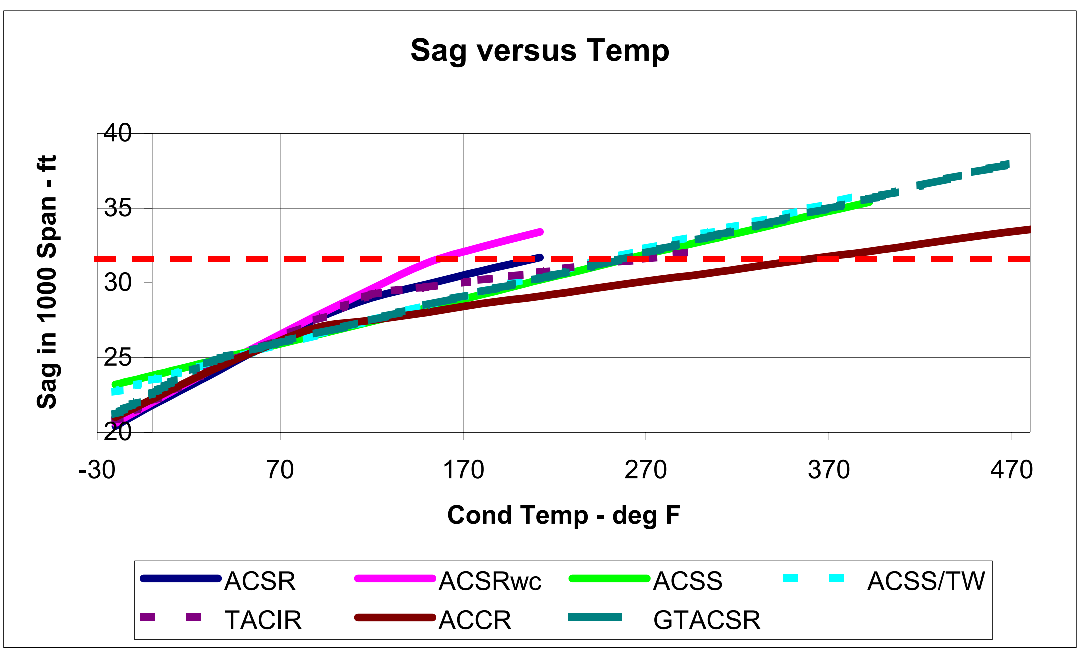

Figure 8-1
Typical Plot of Sag Versus Temperature for Various HTLS Conductor Types

Several observations can be made:

1. Given the sag limit of 31.7 ft, the ACCR conductor with its low thermal elongation attains the highest operating temperature of 370°F. Given the higher conductivity of the composite core and the operating temperature at 188C, the thermal rating is 1550 amperes.

2. ACSS and ACSS/TW both reach the maximum sag at temperatures of 125°C and 120°C, respectively.

3. The higher rating of ACSS/TW (1270 amperes rather than 1190 amperes) is the result of increased aluminum crossectional area. A similar increase in rating would be possible for the other HTLS conductors using TW aluminum wires.

4. With TACIR at its maximum operating temperature of 270°F (132°C), it is below its continuous operation limit of 150°C and has a thermal rating of 1220 amperes.

5. GTACSR reaches the maximum sag limit of 31.6 ft at an operating temperature of 124°C. This corresponds to a thermal rating of 1170 amperes.

For all of these replacement conductors, the maximum operating temperature, determined by maximum sag of 31.6 ft, is well below their continuous operating temperature limit. The thermal rating comparison could be quite different if the line was not clearance limited, if the temperature limit on the original conductor was higher, or if the span lengths were different.

Table 8-1
Summary of Thermal Ratings for Various HTLS Conductors All Having Approximately the Same Diameter

Conductor	Temperature at 31.6 ft sag [deg C]	Thermal Rating [amps] (%increase)	Notes [2]	Maximum tension with 1.0" radial ice at 0°F
Drake ACSR	100	990	Ignores compression in aluminum strands	15300
Drake/ACSS	125	1190 (+20%)		13970 (-9%)
Suwannee/TW/ ACSS [1]	120	1270 (+28%)		16130 (+5%)
Drake ACCR	188	1550 (+56%)	Ignore comp.	15300
Drake TACIR	132	1220 (+23%)	Ignore comp.	15000 (-2%)
Drake GTACSR	124	1170 (+18%)		15300

[1] The maximum tension with heavy ice load is 830 lbs above the original design limit for Suwanee/TW/ACSS and is 1330 lbs below it for Drake/ACSS. Thus the initial tension of the Drake/ACSS replacement conductor could probably be somewhat higher and the thermal rating increased so long as the safety factor under maximum tension was adequate.

[2] The original line design calculations are assumed to have ignored aluminum strand compression. Taking compression into account would increase the high temperature sag of the original Drake ACSR such that the sag clearance limit was reached at about 70oC rather than 100oC and the thermal rating of the line with the original conductor would have to be decreased from 990 to 660 amperes. The calculations for ACCR and TACIR also ignore aluminum compression. Aluminum compression effects are less likely with annealed aluminum and gapped HTLS conductors.

[3] The higher rating of ACSS/TW (1270 amperes rather than 1190 amperes) is the result of increased aluminum crossectional area. A similar increase in rating would be possible for the other HTLS conductors using TW aluminum wires**.**

9 CONCLUSIONS

This report is focused on both commercially available and developing HTLS conductors. While approximate material costs are included, no attempt is made to evaluate the comparative value of these replacement conductors since this is dependent on original design assumptions and power system requirements.

HTLS conductors discussed in the preceding are at various stages of the normal development process. While the mechanical and electrical characteristics of materials such as 1350-H19 aluminum and high strength steel are well known and described in ASTM or IEC standards, materials such as segmented fiberglass/thermoplastic cores and carbon fiber composites are in early stages of development.

Given a simple application of HTLS conductors to a typical clearance-limited transmission line, the high temperature sag and thermal rating of the various commercially available replacement conductors is calculated.

Conductor Choices

Preliminary conclusions and observations about the various types of HTLS conductor is summarized as follows:

1. ACSS and ACSS/TW conductors are commercially available from multiple suppliers in the US. There is an extensive history of utility experience with ACSS and most of the initial concerns about installation and surface roughness problems due to the use of annealed aluminum strands have been proved groundless. The cost premium of these conductors is less than 50% above standard ACSR in most cases. The main limitation with ACSS is its relatively low strength and modulus that limits its use in regions experiencing high ice loads. The use of ACSS/TW can offset this problem to some extent. Little research or development is required beyond improvements in manufacturing and resolution of possible hardware and connector concerns at operating temperatures in excess of 200^{o}C.

2. (Z)TACIR is widely used in Japan. At present, both the Invar steel core and the Zirconium aluminum strands must be imported to the US. The conductor can be stranded in the US though it is not presently available. There is extensive laboratory test data on both the Invar steel core and the Zirconium aluminum alloy wire materials (TAL and ZTAL). It is not clear whether multiple suppliers will develop in the US. There appear to be no special problems with installation and termination of (Z)TACIR. Invar steel is somewhat weaker than conventional steel core wire limiting its use in high ice load areas and compression effects in

the aluminum strands may increase the thermal elongation quoted by the manufacturer. Given the need to import the aluminum and steel alloys from outside the US, the cost of this conductor is likely to exceed twice the cost of ACSR.

3. G(Z)TACSR is commercially available in Japan, can be imported and there is extensive laboratory test data and detailed installation instructions. Outside of Japan, field tests of this conductor are very limited. The installation of this conductor is complex and labor intensive, requiring the unwinding of aluminum wires at each termination and splice. The high temperature CTE has been verified by test and seems likely to be stable with time. The high temperature aluminum alloy increases the strength at low temperatures allowing its use in high ice load areas. The separate movement of the core and aluminum layers, the possible flow of grease at high temperature and long periods of time, and repair methods are possible areas of study.

4. ACCR has been extensively tested by 3M Company under laboratory conditions. Terminations and suspension clamps are available domestically from PPL. A field test of a single 800 ft span was successfully completed recently. The installation of this conductor appears to be reasonably straightforward but may require special large blocks. The composite core is only available from 3M and the Zirconium alloy aluminum strands are currently imported to the US but the conductor can be stranded domestically. Field test installations are required to establish the handling properties, verify the sag behavior at extremely high temperatures and repair methods are possible topics for study. This conductor has an extremely low thermal elongation rate. The combination of alumina composite core wires and zirconium high temperature aluminum alloy yields high rated strength, high modulus, and low resistance. It yielded the largest increase in rating for the example reconductoring case considered earlier in the report.

5. CRAC conductor is in an early stage of development. Laboratory tests have been limited to tests on short samples of fiberglass core. The proposed use of annealed trapezoidal wire aluminum strands in combination with low modulus fiberglass makes its use in high ice load areas unlikely. A splice has been proposed but not demonstrated. There are no commercial sources for the stranded conductor or for fittings. Field testing of CRAC conductor should await further laboratory tests and a selection of particular fiberglass material. Terminations and fittings can only be developed after the fiberglass material properties are certain and test lengths of conductor are available. The light weight and low thermal elongation of fiberglass make this a potentially attractive conductor.

6. ZTACCFR – Carbon fiber reinforced aluminum conductor is not commercially available. The carbon fiber core has been produced in a variety of forms but only in short lengths. It is assumed that the carbon fibers will need to be embedded in an aluminum matrix but this has not been demonstrated. It is also assumed that the outer layers of this conductor would consist of one of the high temperature aluminum alloys such as ZTAL. The negative thermal elongation behavior of carbon fibers combined with low density and “steel-like” tensile strength and modulus make this conductor potentially attractive but the low shear strength of carbon fibers, the problems of corrosion, and high fabrication and material cost are possible drawbacks. The combination of carbon fibers with various matrix materials and in various

configurations is under study. Development of HTLS conductor with a carbon fiber core awaits the completion of studies on the core design.

Conductor Uprating Performance

The best choice of conductor depends on design conditions as is discussed in this report. It is possible, however, to compare the conductors in two simple line uprating situations:

- ***Temperature Limited Line*** - The original transmission line design includes generous ground clearances (i.e. mid-span clearance exceeds 35 feet under everyday unloaded conditions) such that the sag at elevated temperature is not a concern. Here the replacement conductor simply has to operate at high temperature without any significant loss of strength.
- ***Sag Limited Line*** - The ground clearances for the original line design are marginal. The maximum allowable sag of any replacement conductor cannot exceed the present maximum temperature sag.

In both cases it is assumed that the replacement conductor must have approximately the same outside diameter as the original to limit any increase in transverse structure loading. No such limit is placed on the maximum tensions for strain structures.

In the Sag-limited line, the final everyday unloaded sag of all the conductors is assumed to be the same. This ignores possible differences in Aeolian vibration and consequently the need for dampers.

The basic conductor design involves the use of round strands with the exception of ACSS/TW and GTACSR wherein the aluminum strands are trapezoidal. The increased thermal rating of ACSS/TW relative to ACSS (between 5% and 15%) can be realized with any of the other conductor designs if the aluminum strands are manufactured with a trapezoidal crossection.

Table 9-1
HTLS, 1.1 inch OD, Conductor Comparison on the Basis of Equal Everyday and High Temperature Sags

The ground clearance at the maximum conductor temperature shown is the minimum allowed by the NESC Code. Since the OD of all the HTLS conductors is nearly equal to that of the original line, the tranverse structure loads are unchanged.

Conductor Type	Maximum Continuous Temp [deg C]	"Elastic" Modulus for ice&wind loads [Mpsi]	Kneepoint Temperature [Deg C]	Sag change per 10C above kneepoint temp. [ft]	Temperature at original line's minimum ground clearance [deg C]	Relative resistanc e per unit length	Thermal Rating** at Maximum Allowable Sag in 1000 ft span [amps]	Relative cost per unit length
Type 16 ACSR	100C	11.0	60C	0.9	100	1.00	990	1.0
ACSS	200C	7.0	15C	0.9	150	0.98	1190	1.1 – 1.5
ACSS/TW*	200C	7.0	15C	0.9	135	0.90	1270	1.2 – 1.5
TACIR	150C	11.0	40C	0.5	135	1.00	1220	3
ZTACIR	210C	11.0	40C	0.5	135	1.00	1220	5
GTACSR	150C	11.0	15C	0.5	140	0.95	1170	10
ZTACCR	210C	11.0	30C	0.5	210	0.90	1550	10
CRAC	150C	5.0	15C	0.5	90	1.00	900	1.5***
ZTACCFR	210C	11.0	30C	0.1	210	0.90	1550	>10***

* The increase in ampacity obtained by ACSS/TW in this comparison is the result of both increased aluminum crossectional area and increased steel core area that strengthens the conductor. Any of the other conductors listed with the exception of GTACSR could also be fabricated with trapezoidal aluminum strands

resulting in similar increases in ampacity. In this case, where ampacity is determined by sag limitations, the trade-off between steel and aluminum crossectional areas is complex.

** Thermal rating values are calculated for 2 ft/sec crosswind, full noon-time sun, air temperature 40C, and emissivity = absorptivity = 0.5.

*** The cost of these conductors is very uncertain since they are in the earliest stages of development.

Table 9-2
HTLS, 1.1 inch OD, Conductor Comparison on the Basis of Maximum Continuous Operating Temperature

The ground clearance at the maximum continuoustemperature is assumed to be adequate to meet the NESC limits. Since all the conductors have approximately the same OD as the original line, the corresponding tranverse structure loads unchanged.

Conductor Type	Maximum Continuous Temp [deg C]	Maximum Emergency Temp [deg C]	Relative resistance per unit length	Thermal Rating at Max Cont. Temp [amps]	Relative cost per unit length
Type 16 ACSR	100	125	1.00	990	1.0
ACSS	200	230	0.98	1570	1.1 – 1.5
ACSS/TW*	200	230	0.90	1745	1.2 – 1.5
TACIR	150	180	1.00	1325	3
ZTACIR	210	240	1.00	1615	5
GTACSR	150	180	0.95	1315	3
ZTACCR	210	240	0.90	1640	8-12
CRAC	150	150	1.02	1315	1.1 – 1.5***
ACCFR	210	240	0.90	1640	>10***

* The increase in ampacity obtained by ACSS/TW is the direct result of increased aluminum crossectional area not material properties. Any of the other conductors listed with the exception of GTACSR could also be fabricated with trapezoidal aluminum strands and show a similar increase in ampacity.

** Thermal rating values are calculated for 2 ft/sec crosswind, full noon-time sun, air temperature 40C, and emissivity = absorptivity = 0.5.

*** The cost of these conductors is very uncertain since they are in the earliest stages of development.

10
RECOMMENDATIONS FOR TESTING AND FIELD EVALUATION

Historically, manufacturers rather than research groups have developed transmission line conductors. The process often takes at least 20 years from inception to acceptance. This is true of AAAC, ACAR and more recently; ACSS. ACSS was patented in 1969 and only recently has become widely accepted. Few research projects can continue through such an extended period of time.

Conductor development typically involves initial material property tests (tensile strength, minimum elongation, conductivity, etc.) on new materials and manufacturability tests to see if the new material can be drawn to wire and stranded in combination with other wire materials. Finally, stranded conductor sample lengths are tested to derive stress-strain and creep elongation data.

At the conclusion of such laboratory tests, the manufacturer typically arranges field testing with a cooperative transmission company. Field tests involve tension stringing, clipping with recommended support systems, and successful sagging. Subsequent field tests may be performed to verify claimed conductor properties (high self-damping, reduced ice-galloping amplitudes.

The HTLS conductors described in this report are at various points in this development process:

- ACSS is commercially available and needs little additional research or development. The manufacturer, first Reynolds and now Southwire, has performed all necessary laboratory tests to allow sag-tension calculations and it has been used extensively in line upgrading at many utilities.
- The Japanese developers of high temperature alloy conductors with Invar steel cores (ZTACIR and TACIR) and the gapped conductor (GTACSR) have performed many laboratory tests and stress-strain and creep data is available for sag-tension calculations. These conductors have not been used, however, in actual installations in the United States and field testing sponsored by EPRI might be useful to members in accelerating their acceptance or rejection.
- The 3M conductor, ACCR, has been laboratory tested as part of it's development process, but it has only been field tested in a single span at Xcel Energy. Field tests would be useful in identifying this conductor's strengths and weaknesses.
- CRAC and ACCFR are composed of materials, fiberglass and carbon fiber composite, that have not been defined nor laboratory tested. Research on these conductors should emphasize

the definition of material properties including conductivity, tensile and creep elongation properties at high temperature, and corrosion resistance. Until the properties of the reinforcing materials are well-defined there is no need for nor is it possible to execute field tests.

11
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