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VIA MESSENGER

June 14, 2004

Pamela B. Katz
Chairman
Connecticut Siting Council
Ten Franklin Square
New Britain, CT 06051

Re: **Docket 272** - The Connecticut Light and Power Company and The United Illuminating Company Application for a Certificate of Environmental Compatibility and Public Need for the Construction of a New 345-kV Electric Transmission Line and Associated Facilities Between Scovill Rock Switching Station in Middletown and Norwalk Substation in Norwalk, Connecticut Including the Reconstruction of Portions of Existing 115-kV and 345-kV Electric Transmission Lines, the Construction of the Beseck Switching Station in Wallingford, East Devon Substation in Milford, and Singer Substation in Bridgeport, Modifications at Scovill Rock Switching Station and Norwalk Substation and the Reconfiguration of Certain Interconnections

Dear Chairman Katz:

In response to the Siting Council's request at prior hearings for additional information regarding transmission conductors, attached is an original and twenty copies of a report entitled "Practical Application of High-Temperature Low-Sag (HTLS) Transmission Conductors" dated June 11, 2004.

Very truly yours,

Bruce L. McDermott

cc: Service List

Enclosure

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Practical Application of High-Temperature Low-Sag (HTLS) Transmission Conductors

Prepared by:
Dale A. Douglass
Principal Engineer
Power Delivery Consultants, Inc.
June 11, 2004

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Executive Summary

Electrical power systems are designed and operated in order to provide a reliable connection between power generating stations and local distribution substations. During periods of peak normal load and during occasional periods when critical system components of the system may be out of service, the transmission line components of the power system must be able to carry the necessary higher power flows without causing excessive electrical phase shift, voltage drop and or high conductor temperatures. During periods of extreme weather, the line must withstand ice and wind loads on the conductors and structures without mechanical or electrical failure.

80% of all power transmission lines in service today were built with steel reinforced aluminum conductor (ACSR). This type of conductor has proved to be durable and to require minimal maintenance. Many lines, designed for a service life of 40 years, are still in service today after 50 to 70 years. For those instances where power flow must be limited to prevent the overheating of an existing overhead line, replacement of the original power conductor (ACSR) with a "high temperature low-sag" (HTLS) conductor may be advantageous. Note, however, that such conductor replacement must be done with care.

Not all HTLS conductors have been thoroughly tested in both laboratory and by use in the field. Even with those that have been so tested, there may be design limitations, installation and maintenance difficulties, or problems with availability and excessive cost. For example, even with the most successful of the HTLS conductors –ACSS – the line designer must usually accept a reduced safety factor under maximum ice load (e.g. In a typical New England application, with 1 inch of radial ice on the conductor, the tension in ACSS may exceed 50% of the breaking strength while ACSR is less than 40%). Design compromises such as this may be acceptable to obtain a large increase in line thermal capacity (typically more than 30%) without the large capital investment and loss of service needed to replace the existing structures. The argument for using HTLS conductor in new lines is less clear.

In new lines, the cost of maintenance and the expected life of the new line with HTLS conductor must be evaluated relative to conventional ACSR. Among available HTLS conductors, ACSS has the longest history of use (since 1970) and appears to yield maintenance costs and life expectancy that are roughly equivalent to ACSR but NU and UI field experience with ACSS is limited. Certainly, on long lines which are unlikely to reach their conventional thermal capacity because of voltage drop or stability concerns, there appears to be no advantage from using HTLS conductor of any type. Even with shorter lines, which are thermally limited, high thermal capacity can be obtained with the use of a larger conventional ACSR conductor which also yields reduced cost of electrical losses. Less frequently, in the design of short new overhead lines, the use of HTLS power conductors may be economical if the line is only rarely subject to high power flows.

No HTLS conductor, regardless of the reinforcing core material, will alter the electric and magnetic fields produced by the line.

Technical Summary

In existing lines, small increases in thermal rating may be obtained by physical modification of structure attachment points and/or re-tensioning the power conductors to reduce sag. Large increases in line thermal rating usually require replacement of the original power conductors with either larger standard conductors or with HTLS conductors having nearly the same diameter as the original power conductor. HTLS conductors having the same diameter as the original conductor can allow uprating without the need for extensive structure modifications or replacement. However, each line segment must be evaluated on a case by case basis.

Reconductoring with HTLS Conductors - Limitations

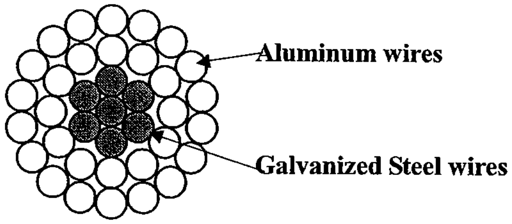
Reconductoring lines with HTLS conductors can increase the thermal rating of the line but there are a number of things that it can't do. For example, as power flows increase, the voltage at the receiving end of the line decreases. Therefore, the power flow is limited to that which yields a 5% voltage drop. Reconductoring the line with a HTLS conductor will not decrease the voltage drop per unit length nor increase the power flow limit due to it.

Similarly, if the flow of power through a particular 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 not help.

No HTLS conductor, regardless of the reinforcing core material, will alter the electric and magnetic fields produced by the line. These fields are dependent upon the physical spacing of the conductors and their geometric arrangement. 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 is simply not possible.

Conventional ACSR versus HTLS Conductors



Normal transmission ACSR ("Aluminum Conductor, Steel Reinforced") power conductors consist of a stranded steel core surrounded by nearly pure aluminum wires which carry most of the electrical current. Being self-supporting, the aluminum and steel strands are subject to tension loads that can reach high levels as wind and ice increase the effective weight of the power conductors. The steel core strength is not affected by high temperature operation and expands thermally at half the rate of aluminum. This limits line sags at high electrical loading. Continuous operation of the aluminum strands is typically limited to 100°C to avoid weakening the aluminum strands over time.

Various types of HTLS conductor are either commercially available, under development, or being researched. All have a high strength core consisting of steel, steel alloy, or a composite material surrounded by multiple layers of aluminum or aluminum alloy. Unlike standard ACSR, the HTLS aluminum wires must have stable mechanical and electrical properties at temperatures as high as 200 to 250°C. The core materials expand at lower rates than the surrounding aluminum in order to limit sag increase at high temperatures. The composite conductor must be inelastic enough to avoid excessive sag and strong enough to avoid tensile failure under severe ice and wind loads.

Utility field experience with HTLS conductors operating at such high temperatures is very limited. Since the aluminum strands expand much faster than the core as the conductor temperature increases and surely go into compression at high temperature, concerns exist regarding the possible resulting increased sag and opening ("birdcaging") of the aluminum strands which could lead to increased corona-induced audible noise and radio interference.

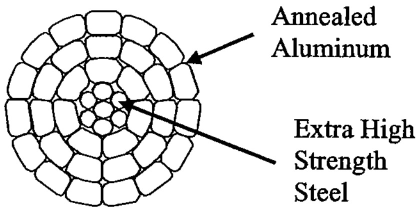
HTLS Conductor Designs

HTLS conductors share certain common characteristics. These include a low thermal elongation rate and stable electrical and physical properties with continuous operation at temperatures as high as 200°C and emergency operation for limited times at temperatures up to 250°C. In general, all HTLS conductors consist of a high strength, low elongation core surrounded by high conductivity strands.

Each HTLS conductor design requires the concurrent development of hardware, connectors, and bundle spacers capable of being operated at these high temperatures as well as surviving normal challenges of Aeolian vibration and ice galloping. No conductor can be said to be commercially available unless connectors and hardware are also available.

ACSS HTLS Conductor

ACSS ("Aluminum Conductor Steel Supported") is a thoroughly tested, commercially available HTLS conductor which is available from multiple vendors in the U.S. ASTM Standards for this conductor have been in existence for 15 years. Introduced in an IEEE paper in 1971, millions of pounds of ACSS have been manufactured and installed since it was first developed. Consisting of ordinary fully annealed aluminum wires stranded over a core of high strength or extra high strength steel, ACSS demands a small cost premium over regular ACSR when compared to other HTLS technologies and is relatively simple to tension string and terminate. Because the outer aluminum strands are annealed, ACSS must be handled and strung with greater care than ordinary ACSR. In addition, special (somewhat longer) compression connectors are normally used to assure a good grip on the relatively soft aluminum strands.



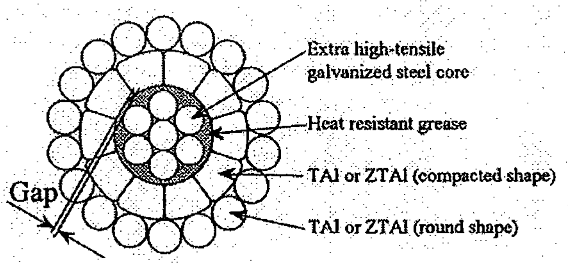
The use of annealed aluminum strands has been shown to greatly increase the mechanical self-damping of ACSS. This allows its installation at smaller everyday sags than ACSR and helps to reduce or prevent vibration fatigue damage in challenging installations such as river crossings.

As shown in the Figure above, ACSS is now commonly available with trapezoidal (TW) aluminum strands. For the same overall conductor diameter, the use of TW aluminum strands either: (a) minimizes conductor electrical resistance for a given steel core, or; (b) maintains conductor electrical resistance with a larger steel core. The choice depends upon the particular uprating application. Trapezoidal strands are also used in other HTLS conductor designs.

Depending upon original design conditions and conductor design, in most cases, reconductoring with ACSS allows an increase of at least 30% in the thermal rating of an existing line.

Since the conductor consists of conventional steel and aluminum, the cost premium, relative to conventional ACSR, is less than 25% in most cases.

Gapped and Invar core Japanese HTLS Conductors



Several HTLS conductors have been developed in Japan. They have been thoroughly tested in both laboratory and field and are commercially available in the United States. All utilize either round or trapezoidal high temperature aluminum alloy strands capable of continuous operation at 200°C. Japanese standards for these conductors exist but there are presently no ASTM or IEC product standards. Reinforcing cores are stranded from normal steel or a special nickel steel alloy ("INVAR") which expands less than normal steel with temperature. (Z)TACIR conductor has the INVAR core.

G(Z)TACSR (shown above) has a normal steel core but is installed with all of the tension in the steel. Special installation procedures and suspension hardware is required. Given the use of special zirconium alloys in both conductors, and the special high nickel content steel alloy in (Z)TACIR, and the present availability from a single supplier, these HTLS conductors command a large cost premium. In most cases, G(Z)TACSR can be used to increase the rating of an existing line by at least 30% but because INVAR steel is not as strong as regular steel, the use of (Z)TACIR in regions such as New England that are subject to occasional high ice loads is not recommended.

The cost premium for GZTACSR is at least 300% relative to normal ACSR. The cost premium for ACIR is probably considerably higher because of the premium for Invar steel.

3M's ACCR HTLS Conductor

3M Corporation has developed an HTLS conductor consisting of the Japanese ZTAL zirconium aluminum alloy over a reinforcing core of ceramic fibers in an aluminum matrix. The conductor has been thoroughly tested in the laboratory and has been field tested in 3 short line sections with two more installations planned for 2004. Special connectors and hardware are available from Alcoa and PLP. Though no ASTM or IEC standards yet exist, it is commercially available through 3M. Production capacity is uncertain.

This conductor has not yet been produced for any large volume transmission line applications. The composite core has very low thermal elongation relative to steel and is about as strong. Unfortunately, as for the Japanese conductors, the conductor commands a large cost premium over regular ACSR. Nonetheless, it should be applicable anywhere in New England and capable of increasing line ratings by at least 30% even when clearances are limited.

Limited cost data indicate that this ACCR conductor commands a cost premium of at least 1000% and as much as 3000% relative to ACSR.

CTC & Showa Carbon-reinforced Resin Core HTLS Conductors

Composite Technology Corp. and Showa Electric are developing HTLS conductors with a carbon-reinforced high temperature thermosetting resin core but the designs are quite different.

The Showa Electric conductor uses round-strand Japanese TA heat resistant aluminum alloy over a stranded composite fiber core. The maximum conductor temperature is limited to 150°C. The Showa Electric TACFR conductor has been thoroughly tested in the laboratory. Field testing was limited to a single 925 ft (282 m) span strung for 2 years under severe weather conditions at a site in Northern Japan. The conductor was not subject to high electrical loads during the field test period. This conductor does not offer any significant advantage when applied to lines in the NU/UI system where the emergency rating ACSR temperature limit is 140°C.

The CTC ACCC conductor uses trapezoidal, annealed aluminum (TW) wires over a single strand composite core. The core is unique among HTLS or conventional conductors because of its much lower flexibility. The core may be described as more of a "rod" than a stranded core. CTC claims a continuous operating temperature of 200°C for this conductor. Samples of the CTC ACCC conductor have recently been subject to a few basic stress-strain and creep tests at Kinectrics. A 21 mile, 115kV line, is supposed to be constructed in Kansas in the next year. No other field tests have been performed.

Both conductors are in an early stage of development and testing. Extensive laboratory tests and field testing is especially important since resins such as these are often subject to deterioration from weather (ultraviolet light, moisture) and high electric fields. There is also justifiable concern about possible corrosion between the carbon fibers and aluminum.

The cost of carbon fiber reinforced resin is likely to be many times that of steel. Given the early stage of development for these conductors, even an approximate cost premium is not known. The low thermal elongation rate of carbon-reinforced resin should result in little or no increase in sag with temperature but the relatively low modulus makes its use in high ice load areas such as New England questionable.

Practical Concerns with HTLS Conductors

Transmission lines consist of commodity materials and are assembled using relatively simple, straightforward methods. The structures and conductors are normally manufactured in accordance with industry product specifications and are available from multiple manufacturers. As a result, transmission lines survive in the open air for periods that typically exceed 60 years while costing less per pound than hamburger.

HTLS Conductor Cost

With the exception of ACSS, HTLS conductor costs from 3 to 30 times as much as standard ACSR. Since 20% to 30% of the cost of a new line is due to conductor, the use of HTLS conductor in new lines may increase the line cost by a factor of 3 or more. Similarly, while the cost of reconductoring is typically taken as one third the cost of a new line, the cost of reconductoring with HTLS conductor could be more than the cost of a new line. Cost of HTLS conductors is important and a key factor in whether these special products are practical or not. It is also an important factor in choosing between HTLS alternatives.

Commercial vs Experimental HTLS Conductors

Bare stranded conductors in overhead power transmission lines experience extremely demanding conditions. Transmission lines are designed for an economic life of 40 years but many of the lines in the Europe and the United States are older than this. The conductors are subject to high winds (hurricanes in Florida, tornados in the mid-west), severe ice buildup that can persist for days or even weeks (especially in the northern US, Canada, and northern Europe), to small magnitude and large magnitude wind-induced motions that can cause strand fatigue, to arc erosion from flashovers, and to sudden increases in electrical power flow (attempting to maintain service during system disruptions) that can drive the conductor temperature from 15°C (60°F) to over 100°C (212°F) in a few minutes.

Rainfall and condensation, especially near seawater, can promote corrosion between different metals such as steel (or other reinforcing materials such as carbon fiber) and aluminum. On the other hand, utilities must above all protect the public safety by maintaining minimum clearances between energized conductors and people, vehicles, and other conductors in lower voltage power lines and communication circuits.

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. After stranding, multiple 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, successful sagging, and application of connectors in the field. Subsequent field tests may be performed to verify claimed conductor properties (high self-damping, reduced sag at high temperature, etc.).

A recent CIGRE questionnaire indicated that over 80% of the transmission conductors in the world are ACSR. This widely available conductor can be ordered with reference to ASTM and IEC specifications, is normally available in quantity (millions of pounds), and can be obtained from multiple suppliers through competitive bidding. As a result, the cost of ACSR is not much more than the cost of aluminum and steel per pound.

The ACSS and ACSS/TW HTLS conductors can also be ordered with reference to ASTM specifications, is normally available in large quantities and can be purchased from at least three different manufacturers in North America. It also can be bought for a small premium over ordinary ACSR. The other types of HTLS conductor cannot be ordered with reference to an ASTM or IEC specification, are available in limited quantities, and can only be obtained from one supplier. This could change, of course, if sales of any of these HTLS conductors reach high levels.

The 3M ACCR conductor and the Japanese G(Z)TACSR and (Z)TACIR conductors may also be considered commercially available since they have been thoroughly tested under laboratory conditions and successfully field tested at multiple locations. Though not as readily available as

ACSS, these conductors can be purchased in reel lengths within reasonable delivery time periods in the United States. None of these three conductors, however, have been used in a major reconductoring project or new line project in the US, perhaps as a result of the high cost premium associated with both.

The TACFR conductor is not commercially available in the US. It has undergone only limited laboratory and a single span field test in Japan. The manufacturer of ACCC (Composite Technologies Corporation) claims that the conductor is commercially available but laboratory tests have been limited to a handful and there have been no field tests. While promising from the point of view of low thermal elongation, the use of carbon-reinforced resin as the main strength member (the aluminum is annealed) is a radical departure from steel and concerns about corrosion and long term survival under field conditions have not been answered.

Conductoring and Reconductoring with HTLS Conductors

NU/UI calculates line thermal ratings for ACSR under normal and emergency system conditions, tolerating higher temperatures for short duration electrical loading events. The maximum allowable ACSR temperatures are 100°C for continuous loads; 140°C for emergency loads of less than 24 hours. Certain lines, having sufficient electrical clearance, are operated to 180°C during emergencies.

HTLS conductors can be operated at higher temperatures (~200°C for continuous loads and 250°C for emergencies of less than 24 hours) than NU/UI presently allows with ACSR. The increase in line rating, gained through the replacement of ACSR by HTLS conductors, depends on the temperature presently allowed for ACSR. As shown in the following table, NU and UI use a continuous limit of 100°C and an emergency temperature limit of 140°C. These temperature limits are at the upper bound of typical industry practice with ACSR. As such, the increase in line rating is generally less than that obtained with more conservative limits on ACSR.

Given the 100°C and 140°C temperature limits on ACSR, if operated to the manufacturer's recommended maximum temperatures, with suitable high temperature connectors and hardware, HTLS conductors could yield line rating increases of 40% to 80% with the same diameter as the original conductor.-

Conductor Name	Continuous Rating (amps)	Emergency Rating (amps)	15 min Emergency (amps)
Bittern ACSR	1490 @100C	1920 @140C	2180 @140C
Bittern ACSS	2458 @200C	2787 @250C	3059 @250C
Potomac ACSS/TW	2725 @200C	3103 @250C	3523 @250C

In new lines, however, the construction cost savings from using HTLS conductors may not be justified if normal power flows are high and the cost of electrical losses is consequently large. In that case, the application of a larger, lower resistance standard ACSR conductor may be a better solution for a new line.

In reconductoring existing lines with HTLS power conductors, low electrical clearance margins may limit the maximum allowable temperature of the replacement conductor to less than 200°C and reduce the possible increase in thermal rating. In clearance limited uprating situations, the type of HTLS conductor which works best is a complex function of the core thermal elongation rate, mechanical self-damping, the stiffness and strength of the HTLS conductor, and both the original conductor type and its tension design limits. The HTLS conductor with the lowest thermal elongation rate (ACCC) does not always result in a greater increase in thermal rating. In many cases, the use of ACSS yields an adequately large increase in thermal rating and its low cost and commercial availability make it preferable to less well-tested, more expensive HTLS conductor alternatives.

Conclusions

In those cases where normal or emergency power flow is constrained by the thermal rating of an overhead line, and reconductoring with a HTLS conductor is necessary to obtain a large increase in rating, ACSS or ACSS/TW appears to be the best choice. It is commercially available from three domestic suppliers, has been proven safe and reliable through decades of use in many different line locations, commands only a modest cost premium over standard ACSR (less than 25%), can be specified by citing an ASTM manufacturing standard, uses commercially available connectors and hardware, and can be installed by normal tension stringing equipment and methods.

A second commercially available HTLS conductor which should produce similar increases in line rating is GZTACSR. This HTLS conductor is stronger and stiffer than ACSS but it is available from only one supplier, commands a cost premium of at least 200% over ACSR, and requires major changes in termination, stringing and sagging procedures.

Evaluation of several uprating examples in the report leads to the conclusion that none of the HTLS conductors is clearly superior in all reconductoring situations. Reconductoring an existing line with any of the HTLS designs seems capable of increasing the line rating but the relative advantages of other HTLS conductors compared to ACSS and GZTACSR are typically modest. The 3M ACCR conductor has been thoroughly tested but its high cost does not seem justified by any major advantage over these conductors. The CTC ACCC conductor does seem to have some advantage in terms of thermal elongation but this advantage does not seem sufficient to justify the purchase of an untested and unproven conductor.

Definitions

AAAC - All Aluminium Alloy Conductor.

ACAR - Aluminium Conductor Alloy Reinforced.

ACCC – CTC's designation for their (Annealed) Aluminum (Carbon-reinforced resin) Composite Core Conductor.

ACCR – 3M's designation for their Aluminum Conductor (Ceramic-reinforced Aluminum) Composite Reinforced.

ACFR – Showa Electric's designation for Aluminum Conductor Carbon Fiber Reinforced.

ACSR - Aluminium Conductor Steel Reinforced.

ACSS - Aluminium Conductor Steel Supported - A stranded conductor made up of fully annealed aluminium strands over a core of steel strands.

Ampacity - The ampacity of a conductor is that maximum constant current which will meet the design, security and safety criteria of a particular line on which the conductor is used. In this brochure, ampacity has the same meaning as "steady-state thermal rating."

Annealing - The process wherein the tensile strength of copper or aluminium wires is reduced at sustained high temperatures.

ASTM - American Society for Testing and Materials.

CFCC – Showa Electric's designation for Carbon Fiber Composite Cable (made up of carbon fiber and resin) that is the core of their ACFR conductor..

Electrical Clearance - The distance between energised conductors and other conductors, buildings, and earth. Minimum clearances are usually specified by regulations.

EC (grade aluminium) - Electrical Conductor grade aluminium also called 1350-H19 alloy or A1.

EHS Steel - Also designated S3. Extra High Strength steel wires for ACSR.

G(Z)TACSR - Gap- type (Z)TAL aluminium alloy Conductor, Steel Reinforced.

HS Steel - Also designated S2. High Strength steel core wires for ACSR.

I.A.C.S. or IACS - International Annealed Copper Standard.

IEC - International Electrotechnical Commission.

Invar Steel - A steel core wire made with high Nickel content to reduce the thermal elongation coefficient.

Knee-point Temperature - The conductor temperature above which the aluminium strands of an ACSR conductor have no tension or go into compression.

Maximum Allowable Conductor Temperature - The highest conductor temperature at which an overhead power line can be safely operated.

RBS - Rated Breaking Strength of conductor. A calculated value of composite tensile strength, which indicates the minimum test value for stranded bare conductor. Similar terms include Ultimate Tensile Strength (UTS) and Calculated Breaking Load (CBL).

Ruling (Effective) Span - This is a hypothetical level span length wherein the variation of tension with conductor temperature is the same as in a series of suspension spans.

SDC - Self-Damping Conductor is an ACSR conductor wherein the aluminium strands are trapezoidally shaped and sized such that there is a small gap between layers to allow impact damping of aeolian vibration.

T2 - Twisted Pair conductor wherein two ordinary round stranded conductors are twisted around each other to enhance mechanical stability in wind.

TACIR - TAL Aluminium Alloy Conductor reinforced with an Invar steel core.

TACFR – Thermal resistant Aluminum conductor Carbon Fiber Reinforced consists of TAL wires stranded around a CFCC core.
TACSR - TAL Aluminium Alloy Conductor reinforced by a conventional stranded steel core.

TAL – ("Thermal-resistant aluminium") An aluminium zirconium alloy that has stable mechanical and electrical properties after continuous operation at temperatures of up to 150°C.

Thermal Rating - The maximum electrical current, which can be safely carried in overhead transmission line (same meaning as ampacity).

TW conductor - A bare overhead stranded conductor wherein the aluminium strands are trapezoidal in cross-section.

Uprating - The process by which the thermal rating of an overhead power line is increased.

Weight - This brochure generally uses conductor in weight per unit length. Mass per unit length can be obtained by dividing by the acceleration of gravity (approximately 9.81 m/sec^2).

"Worst-case" weather conditions for line rating calculation - Weather conditions which yield the maximum or near maximum value of conductor temperature for a given line current.

ZTAL – ("Super Thermal-resistant aluminium") An aluminium zirconium alloy that has stable mechanical and electrical properties after continuous operation at temperatures of up to 200°C.

ZTACIR - ZTAL aluminium alloy conductor reinforced by an Invar steel core.

Why limit Power Flow through Overhead Lines?

Power system operators must keep the power flow through overhead lines and other power equipment below certain maximum power flow levels in order to ensure the public safety, maintain the reliability of the transmission system, and to avoid damage to critical power equipment. These maximum allowable power levels are commonly referred to as the equipment's rating. When multiple types of power equipment are arranged in series making an electrical circuit, then the circuit rating is the minimum of the series components.

Accommodating Customer Power Loads on Critical Circuits

If the system operator is forced to reduce power flow very quickly (e.g. less than 10 minutes), in many cases, the only effective means is by shedding load (disconnecting customers). Load shedding is dangerous, costly, and adversely affects the lives and commerce of customers. In order to avoid this sort of drastic action, transmission asset managers and operators prefer to increase the rating of existing circuits, to build new circuits with adequate capacity, or to reduce load levels in a more controlled fashion.

If the need to reduce circuit load is foreseen through system analysis planning studies, the transmission asset manager can use "passive" or "active" methods as an alternative to load shedding. An example of a passive method would be the addition of a "parallel" transmission circuit to carry a portion of the customer load. The new circuit typically adds to the overall capacity and reliability of the system as well as reducing the load on existing circuits that would otherwise be overloaded. Since the added components are entirely new and separate, they may be expected to increase the overall system reliability and reduce maintenance.

An active method of power flow reduction might involve the installation of a phase angle regulating transformer or other flexible ac transmission device that allow the operator to change critical transmission system power flows. Unlike the addition of new parallel circuits, however, active load reduction devices will cause increased loading of other system circuits and may cause overloads elsewhere.

Increasing Ratings in Overhead Line Circuits

Ratings for overhead transmission circuits are specified by the asset owner to limit one or more of the following:

Electrical Limits

- Electrical phase shift (Stability concerns)
- Voltage Drop (Adequate voltage at load bus)
- Excessive Contingency loadings of other "parallel" circuits

Thermal-Mechanical Limits

- Power conductor temperature (Electrical clearance & annealing of aluminum)
- Critical temperatures in Substation terminal equipment

Economic Issues

- Cost of electrical losses in the conductors

The "rating" of an overhead line circuit is the minimum of the ratings corresponding to each of these constraints. For example, the current on an overhead line may be limited to 1150 amperes (the line's rating) while the substation terminal equipment may be limited to 1200 amperes. In this case the overhead transmission circuit rating is 1150 amperes. If the line is modified by replacing the existing conductor, and its rating is increased to 1500 amperes, the rating of the overhead circuit is now limited by the substation terminal equipment to only 1200 amperes.

Similarly, increasing the circuit rating by raising the line rating and replacing substation terminal equipment may shift the limiting constraint on power flow to loading of other circuits. Since it is common to find that removing one of these constraints on power flow changes the limiting constraint, a large increase in the circuit rating may require multiple actions to replace, add or modify power equipment in multiple circuits. As a general rule, NU/UI attempts to maintain the overhead line as the limiting element in the circuit.

Electrical Constraints on Power Flow

When power flows in overhead transmission circuits, the phase angle between the sending end and receiving end voltages increases with the length of the line. The maximum allowable power flow related to this phase shift is inversely proportional to the line's inductive reactance. The limit on power flow with regard to such "stability" concerns is characterized by the "surge impedance loading" of the line. Normally, stability limits on power flow are much lower than thermal limits but only apply to long lines (e.g. greater than 200 miles). The choice of power conductor size and type has little or no impact on such limits since line reactance is determined by phase spacing and configuration.

In addition to the increase in phase shift along the line, the magnitude of the sending end voltage decreases. A typical limit on voltage magnitude drop is 5%. Power flow limits determined by voltage drop are usually more restrictive than stability limits but less restrictive than thermal rating limits. Voltage drop is usually a concern with moderately long lines (e.g. 50 to 200 miles). The choice of size and type of power conductor also has little impact on voltage drop power flow limits since line reactance is again the major factor.

The power transmission system is interconnected for reliability. This allows for multiple transmission paths to supply critical load centers. While this is a very important feature of modern power systems, it also results in a limitation on the power flow in any overhead line circuit – the power flow in any circuit cannot be so high that the loss of that circuit results in the overload of another circuit. This is a primary limitation on power flow through EHV (345 kV and up) circuits since they are capable of carrying such high levels of power relative to other lower voltage lines.

Mechanical-Thermal Constraints

In a region such as Connecticut, where line lengths between terminals, are relatively short, power flow on 115kV lines is typically limited by the line's thermal rating rather than by electrical phase shift or voltage drop ratings.

The following table summarizes a comparison of electrical and thermal ratings for overhead lines of different operating voltages and varying lengths:

Table 1 - Comparison of SIL, voltage drop and thermal limits for overhead lines

Line kV	Surge Impedance	SIL (Surge Impedance Loading)*	%Voltage Drop at Typical NU/UI Thermal Rating**		Thermal Rating***	Thermal Rating with HTLS****
kV	Ohms	MVA	10 mi	50 mi	MVA	MVA
115	350	40	0.8%	>10%	240-290	360-580
345	280-370	325-420	0.3%	6.2%	1430	2100-2860

* - for a 44° phase shift with no series compensation

** - 5% voltage drop is the assumed limit

*** - Typical NU/UI Rating at a Maximum temp of 140°C.

**** - Typical HTLS Rating for NU/UI rating conditions and a Maximum temp of 200°C.

It can be seen from Table 1 that for 10 mile long lines, power flow is limited by the line's thermal rating and not by voltage drop. Alternatively, for 50 mile long lines, increasing the present thermal rating would accomplish nothing unless equipment such as shunt capacitors were installed to reduce voltage drop.

What may also be seen from the table is the large difference in both SIL and thermal rating between the 115 and 345 kV lines. The difference in SIL is proportional the ratio of the line voltages squared. The difference in thermal rating is due to the three-fold increase in voltage and the use of two conductors per phase at 345KV.

What is not evident from Table 1 is that there may be other constraints on power flow. For example, the power flow on a 345kV circuit may need to be limited in order to avoid overloading certain 115kV circuits during an outage. It may be difficult to find enough alternate capacity to handle the loss of a 345kV line carrying 2500 MW if the alternate paths are only 115kV lines, each with a thermal rating of between 240 and 580 MW.

Economic & Environmental Constraints

Electric & Magnetic fields

This report considers the thermal uprating of existing lines by replacing the original conductors but 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 with the higher line currents.

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.

Economic Cost of Losses

Operation of lines at high temperatures is a clear indication that electrical losses are significant during periods of high load and corresponding high conductor temperatures. If high loads occur on a daily basis, then the use of HTLS conductor to increase the thermal capacity of the line may avoid electrical clearance infringement and loss of conductor strength but the cost of electrical losses over the life of the uprated line may be prohibitive. If high loads occur only occasionally as the result of certain low probability system contingencies, then the use of HTLS conductors to increase the thermal rating of the line may be an excellent low cost solution.

The cost of electrical losses should be considered as part of the process of evaluating up-rating alternatives. 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.

Why Thermal Overloads Occur?

Transmission lines must have sufficient thermal capacity to handle both normal and post-contingency (emergency) loads. When, through a process of power system analysis, the thermal rating of a line is found to be inadequate, the choice of uprating method depends upon the frequency of occurrence, the amount by which the load exceeds the line rating, and the duration of the overload. In this section of the report two overload scenarios are considered: the normal circuit load exceeds the continuous rating of the line: or the post-contingency (emergency) load exceeds the emergency rating of the line.

"Normal" Overload

Certain transmission lines, in any system, may require uprating because of growth in normal load. For example, consider a line supplying power to a rapidly growing suburban area. In this overload situation, the frequency of overloads is high (e.g. daily for the summer peak load period), the duration can be for several hours each day, and the amount by which the load is projected to exceed the line rating in a few years may be no more than 5% to 10%. If the rate of increase in normal power flow is modest, then a modest increase in thermal line rating may suffice for many years. If the line is long, the electrical losses generated by daily high normal loads make the cost of electrical losses a consideration in this uprating case.

If the relatively high cost of electrical losses per mile is not considered, then suitable uprating solutions in this loading case may involve the use of dynamic rating and monitoring methods, minor physical modifications to the line to increase clearance, and possible re-tensioning of the existing conductor combined with reinforcement of angle and dead-end structures.

If the high cost of electrical losses per unit length is excessive, then replacement of the existing line with a new line utilizing larger conductors may be justified if regulatory agreement can be obtained.

"Post-Contingency" Overload

Certain transmission lines may require uprating because of high electrical loads which only occur following the loss of a major system component (e.g. generator or another transmission line). Such overloads are usually infrequent, the duration of high power flows on the line is probably less than 24 hours. The amount of power flow on the lines can be quite large. For example, in a transmission system consisting largely of 345 kV and 115kV lines, under normal operating conditions, the bulk of power flow is over the 345kV lines because of their relatively low "per unit" electrical impedance (about 10% of a 115kV line). Given a system contingency (e.g. the loss of a 345 kV line), the lower voltage lines and associated substation equipment can become heavily loaded as the system operator takes steps to control pre-contingency and post-contingency load levels on heavily loaded lines and substation facilities.

In considering an appropriate method of line uprating, to deal with such post-contingency loadings, simple marginal uprating methods (dynamic rating, re-tensioning, etc.) may not yield a sufficiently large increase in line rating. Given the need for a large increase in line rating and the relatively low cost of electrical losses under normal conditions, reconductoring the line with high temperature low sag conductor may be reasonable since the existing structures can be re-used and regulatory approval may be relatively straightforward.

Increasing the thermal rating of an existing line (Uprating)

Given "worst-case" weather conditions used for rating purposes, the maximum allowable temperature of a line's energized conductors determines the thermal rating of an overhead line. The maximum allowable sag (for which the minimum ground clearance is maintained) and the maximum allowable loss of tensile strength of this conductor (over the life of the line), determine the maximum allowable conductor temperature. Thus the thermal rating of any overhead line is determined by the relationship of current and conductor temperature.

NU/UI Rating Assumptions

If the increased structural loads resulting from the use of larger diameter replacement conductor are acceptable, it may be possible to increase the thermal rating of the line and to reduce the normal electrical losses by using a larger conductor which has lower electrical resistance.

In many cases, however, the operation of existing line conductors at higher temperature is not possible and the use of a larger diameter replacement conductor may require extensive structural modifications that are prohibitively expensive, require extensive circuit outage times, or unacceptable to the public. In such cases, the use of a smaller cross-section replacement conductor, tolerant of operation at high temperatures, may be an attractive solution if the cost of electrical losses is acceptable. Of course, the high temperature conductors must also exhibit relatively low sag at high temperature in order to maintain electrical clearances.

NU/UI calculates three types of thermal rating for overhead lines:

- Normal Rating with a maximum conductor temperature of 100°C.
- Emegency Rating with a maximum conductor temperature of 140°C (180°C in certain limited line sections).
- 15 minute Emergency Rating with standard seasonal weather conditions. For summer, these worst-case weather conditions are air temperature 37.8°C, solar heating rate 5.59 watts/ft/inch, and a wind speed of 3 ft/sec perpendicular to the line. The continuous rating of "Bunting" ACSR (outside diameter 1.345 inches) is 1490 amperes.

The Emergency thermal rating is based on the same worst-case weather conditions with a higher conductor temperature of 140°C. For summer, the "Long Term Emergency" (24 hour emergency) rating of the Bunting conductor is 1922 amperes. Emergency loadings in excess of the standard rating of 1490 amperes is limited to 24 hours in order to limit the loss of conductor strength of this ACSR conductor.

Typical NU/UI Line Ratings

For an NU/UI transmission line with ACSR conductors and adequate electrical clearance at high temperature, the maximum allowable conductor temperatures presently in use are:

- 100°C for **continuous** ratings.
- 140°C for up to 24 hour long-time emergency (**LTE**) ratings.
- 140°C for 15 minute short time emergency (**STE**)ratings assuming a pre-load equal to 75% of the continuous rating.

The weather conditions used for line rating calculations by NU/UI are:

- Air temperature of 37.8°C (100°F) for summer.

- Solar heating 5.59 watts/ft per inch of conductor diameter.
- Wind speed of 3 ft/sec perpendicular to the conductor.
- Elevation is 0 ft.
- Emissivity = 0.75

The calculations of thermal rating in this report are performed using the RateKit calculation program which is based upon the IEEE 738-1993 "Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductor". NU/UI uses a very similar but not identical calculation method. For NU/UI standard conductors, the NU/UI "book" rating is listed as well as the rating calculated with the RateKit program. The rating of HTLS conductors are calculated with RateKit.

The ratings for Bittern ACSR calculated by RateKit are compared to NU/UI book ratings in Table 2

Table 2 - Comparison of Thermal Ratings for Standard Bittern ACSR and Bittern ACSS, an HTLS conductor.

Conductor Name	Continuous Rating	Emergency Rating	15 min Emergency	Calculation Method
Bittern ACSR	1490 @100C	1920 @140C	2180@140C	NU/UI Book
Bittern ACSR	1490 @100C	1910 @140C 2232 @180C	2180 @140C 2576 @180C	RateKit (IEEE 738-1996)

Uprating Lines with Larger Conductors

Figure 1 illustrates this relationship for three different sized conductors with typical "worst-case" weather conditions. The relationship between the current and temperature was calculated by the use of the IEEE thermal rating method described in P738-1993, with typical values for conductor resistance and dimensions. The assumed weather conditions used by NU and UI are described in the caption of Figure 1.

From Figure 1, it can be seen that a thermal rating of 1000 amperes is not unique to any conductor aluminium cross-sectional area. It may be obtained by using a conductor with an aluminium cross-sectional area of (A) 800-mm^2 (1590 kcmil) at a conductor temperature of 70°C, (B) 400-mm^2 (795 kcmil) conductor at 100°C, or (C) a 200-mm^2 (397.5 kcmil) conductor at 200°C.

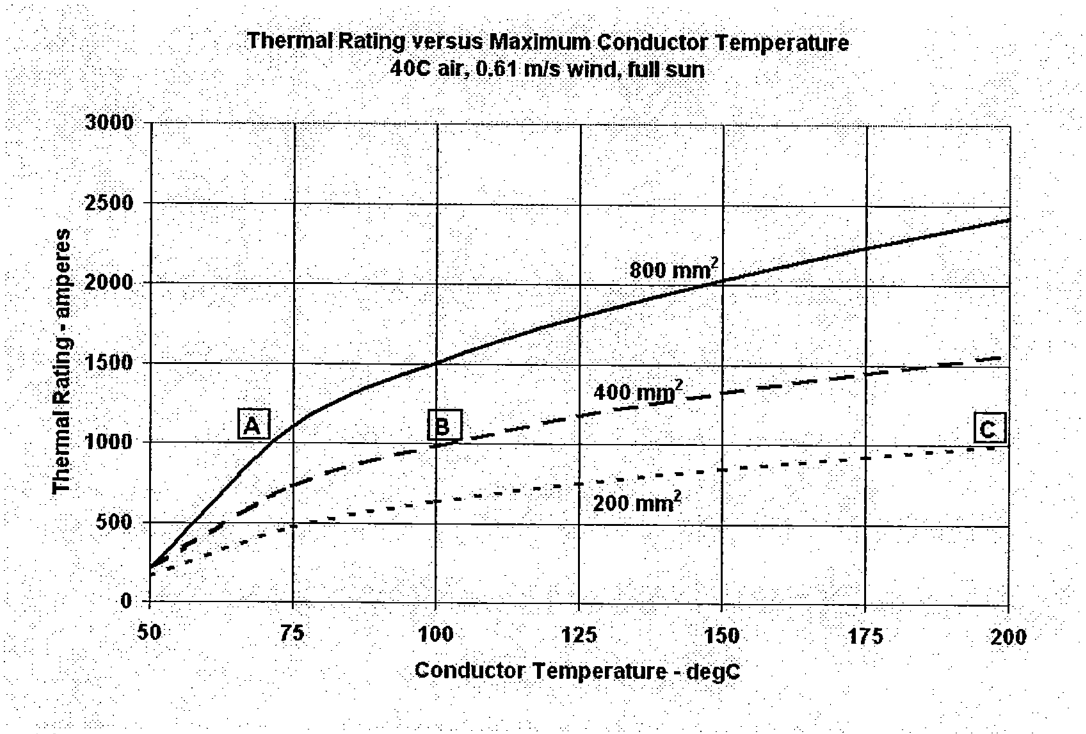


Figure 1 - Line thermal rating as a function of maximum allowable conductor temperature and conductor cross-sectional area

Clearly, if higher electrical losses are acceptable, and limits on loss of tensile strength and maximum sag can be met, the smaller conductors operating at higher temperature can yield the same thermal rating as large conductors at more conventional temperatures.

If the maximum allowable operating temperature of the existing line conductors is modest, it may be possible to accommodate operation at somewhat higher temperature by re-tensioning the original conductor or by raising attachment positions. In this manner, the line's thermal rating can be increased without replacing the conductors.

Uprating Lines by Increasing Maximum Conductor Temperature

The purpose of reconductoring an existing transmission line with HTLS conductor is to increase the line's continuous and emergency thermal ratings. Thus during severe system disruptions, higher power flows can be sustained without damaging the conductors or violating electrical clearance requirements.

Increase in Rating with HTLS Alternatives

If the present ACSR conductors used by NU/UI are replaced with an HTLS conductor having the same crossectional area of aluminum, then the thermal rating would be increased because of the higher allowable operating temperature of HTLS. For example, Bittern/ACSS has the same diameter as Bittern ACSR (1.345 inches), a common conductor in the NU/UI transmission system, but according to the manufacturer's recommendations, can be operated at temperatures of 200°C continuous and 250°C emergency. As shown in Table 3, the increased operating temperature of ACSS yields the following increase in thermal rating:

2458 amperes continuous (65% higher than ACSR at 100°C)
2787 amperes Emergency (46% higher than ACSR at 140°C)
3059 amperes 15 min Emergency (37% higher than ACSR at 140°C)

ACSS and other HTLS conductors are also available with trapezoidal aluminum (TW) strands. The use of TW aluminum yields a lower resistance without increasing the outside diameter. An existing Bittern ACSR conductor can be replaced with a Potomac ACSS/TW conductor which has the same diameter as Bittern ACSR but a resistance of 0.0613 Ohms/mi at 25°C instead of 0.0764, a reduction of 20%. As is also shown in Table 3, the increased operating temperature of ACSS and the reduced resistance resulting from the use of TW wires, yields the following increases in thermal rating:

2725 amperes continuous (+83% higher than ACSR at 100°C)
3103 amperes Emergency (+62% higher than ACSR at 140°C)
3523 amperes 15 min Emergency (+62% higher than ACSR at 140°C)

Table 3 - Comparison of thermal ratings for Bittern ACSR, Bittern ACSS, and Potomac ACSS/TW.

Conductor Name	Continuous Rating	Emergency Rating	15 min Emergency	Calculation Method
Bittern ACSR	1490 @100C	1920 @140C	2180 @140C	NU/UI Book
Bittern ACSR	1490 @100C	1910 @140C 2232 @180C	2180 @140C 2576 @180C	RateKit (IEEE 738-1993)
Bittern ACSS	2458 @200C	2787 @250C	3059 @250C	RateKit (IEEE 738-1993)
Potomac ACSS/TW	2725 @200C	3103 @250C	3523 @250C	RateKit (IEEE 738-1993)

The higher ratings shown for ACSS and ACSS/TW in Table 3 are due to its ability to operate at higher temperatures without affecting its mechanical or electrical properties and, in the case of ACSS/TW, to the 20% lower resistance due to the increased aluminum crossectional area. Other types of HTLS conductor (which utilize resin or metal composite cores in place of steel) yield similar possible increases in thermal rating due to operation at higher temperature and, when TW aluminum is used, due to reduced resistance.

It should be noted that, although all HTLS conductors are capable of operating at higher temperatures than standard ACSR conductors, when used to reconductor an existing line, the HTLS conductors must be able to operate at these high temperatures without exceeding the original allowable high temperature sags. In brief, HTLS conductor must not only be able to operate at temperatures on the order of 200°C but they must do so with no more sag than the conventional conductor at a lower operating temperature. Thus the name – High Temperature Low Sag – conductor.

Substation Terminal Equipment – Limit on Line Uprating

The large increases in thermal line rating which are possible with the application of HTLS conductor are likely to exceed the rating of non-line power equipment such as substation bus, line disconnects, wave traps, and circuit breakers. Unless these components are also replaced, the increase in circuit thermal rating realized from the application of HTLS conductors will be much less than the increase in line rating.

Using HTLS Conductors in New Lines

The design constraints on conductor selection for new lines are considerably less restrictive than those governing the uprating of existing lines. For example, there is no need to maintain a certain set of structure loads in order to avoid rebuilding existing structures and there are no problems regarding the maintenance of electrical ground clearance at high temperature since the structure height can be raised or lowered as part of the design process.

Choosing the conductor size

In a new line, one of the concerns in selection of power conductor size is the cost of electrical losses over the life of the line. The other concern against which electrical losses must be balanced is the cost of materials and construction labor. The cost of electrical losses over the life of the line can be reduced by using a larger (lower resistance) power conductor but this increases the cost of the conductors, structures, and any foundations because of higher wind and ice loads.

Given the phase configuration, a minimum power conductor diameter is necessary to avoid unacceptable levels of corona-induced noise. A single large conductor per phase of a 345 kV line may keep losses sufficiently low but produce excessive audible noise and radio interference when compared to a two-conductor bundle of smaller conductors.

Evaluating the use of HTLS Conductor

The commercial availability of certain HTLS conductors offers the line design engineer new options regarding the selection of power conductors for new lines as well as for reconductoring existing lines. Consider for example the choice of Bunting 1192.5 kcmil ACSR versus Bunting ACSS. These conductors have essentially the same resistance at the same temperature and thus the same cost of electrical losses per mile of line and the same wind and ice loads per unit length of conductor. The thermal rating of the line, however, is quite different. Using NU/UI's rating assumptions, the continuous thermal rating of Bunting ACSR at 100°C is 1490 amperes whereas the thermal rating of Bunting ACSS at 200°C is 2452 amperes, a difference of 65%. The emergency ratings 140°C and 250°C, respectively, are 1920 and 2790 amperes, a difference of 45%.

The increased operational flexibility obtained from the higher thermal ratings need to be balanced against the cost premium for the ACSS conductor and any increase in structure cost required to provide clearance at the higher operating temperature of ACSS. As an example, consider the sag-tension calculations shown for an 800 ft span of Bittern ACSR and Bittern ACSS. In both cases the maximum final tension under NESC Heavy conditions is 10,000 lbs. Given the high self-damping of ACSS, the manufacturers recommend allowing its unloaded everyday tension to be as high as Code limits (33% initial and 25% final at 60F). Because of the lower thermal elongation of ACSS, the sag of Bittern ACSS at 250°C is slightly less than the sag of Bittern ACSR at 140°C. It appears that in this particular case, the maximum conductor tension (i.e. 10,000 lbs) and the maximum sag (33.75 ft) is the same for Bittern ACSR and ACSS so that the structure costs would be approximately the same.

ALUMINUM COMPANY OF AMERICA SAG AND TENSION DATA
HTLS Project Sag-Tension Calculations
Conductor BITTERN 1272.0 Kcmil 45/ 7 Stranding ACSR

```
Area=    1.0680 Sq. in    Dia= 1.345 in    Wt= 1.434 lb/f   RTS=   34100 lb
Data from Chart No. 1-957
English  Units
Using Exact Catenary Equations

Span=     800.0 feet    NESC Heavy Load Zone
Creep IS a Factor     Rolled Rod
    Design Points                      Final                   Initial
 Temp   Ice   Wind   K   Weight   Sag  Tension  RTS       Sag  Tension  RTS
   °     in   psf  lb/f  lb/f     ft     lb     %          ft     lb     %
   0.   .50  4.00  .30  2.997   24.06   10000. 29.3*    22.92   10493. 30.8
  32.  1.00   .00  .00  4.350   27.16   12871. 37.7     26.60   13143. 38.5
  32.   .50   .00  .00  2.581   25.04    8279. 24.3     23.51    8812. 25.8
 -20.   .00   .00  .00  1.434   20.44    5628. 16.5     18.16    6329. 18.6
   0.   .00   .00  .00  1.434   21.59    5328. 15.6     19.29    5960. 17.5
  60.   .00   .00  .00  1.434   24.84    4635. 13.6     22.55    5103. 15.0
 120.   .00   .00  .00  1.434   27.81    4146. 12.2     25.58    4504. 13.2
 167.   .00   .00  .00  1.434   29.96    3851. 11.3     27.79    4148. 12.2
 212.   .00   .00  .00  1.434   31.91    3618. 10.6     29.79    3872. 11.4
 257.   .00   .00  .00  1.434   33.21    3478. 10.2     31.69    3643. 10.7
 285(140C)    .00  .00  1.434   33.75    3423. 10.0     32.83    3518. 10.3
 356.   .00   .00  .00  1.434   35.10    3293.  9.7     35.10    3294.  9.7
 392.   .00   .00  .00  1.434   35.78    3232.  9.5     35.77    3232.  9.5
 437.   .00   .00  .00  1.434   36.61    3160.  9.3     36.61    3160.  9.3
 482.   .00   .00  .00  1.434   37.43    3092.  9.1     37.43    3092.  9.1
*  Design Condition
```

ALUMINUM COMPANY OF AMERICA SAG AND TENSION DATA
HTLS Project Sag-Tension Calculations
Conductor BITTERN/ACSS 1272 Kcmil 45/ 7 Stranding ACSS

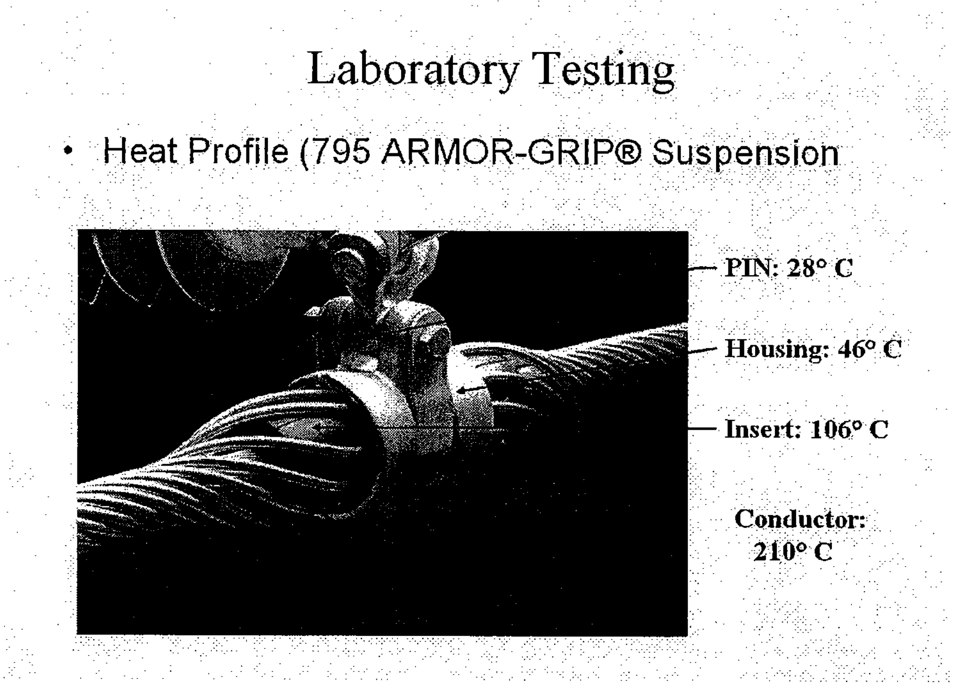
```
Area=    1.0678 Sq. in    Dia= 1.345 in    Wt= 1.432 lb/f   RTS=   24000 lb
Data from Chart No. 3-951
English  Units
Using Exact Catenary Equations

Span=     800.0 feet    NESC Heavy Load Zone
Creep is NOT a Factor
    Design Points                      Final                   Initial
 Temp   Ice   Wind   K   Weight   Sag  Tension  RTS       Sag  Tension  RTS
   °     in   psf  lb/f  lb/f     ft     lb     %          ft     lb     %
   0.   .50  4.00  .30  2.995   24.77    9709. 40.5     22.34   10758. 44.8
  32.  1.00   .00  .00  4.348   27.79   12579. 52.4     27.79   12579. 52.4
  32.   .50   .00  .00  2.579   25.74    8048. 33.5     21.19    9766. 40.7
 -20.   .00   .00  .00  1.432   21.30    5393. 22.5     13.96    8219. 34.2
   0.   .00   .00  .00  1.432   22.43    5124. 21.3     14.48    7920. 33.0*
  60.   .00   .00  .00  1.432   24.81    4635. 19.3     16.45    6976. 29.1
 120.   .00   .00  .00  1.432   26.08    4412. 18.4     18.93    6065. 25.3
 167.   .00   .00  .00  1.432   27.06    4252. 17.7     21.08    5450. 22.7
 212.   .00   .00  .00  1.432   28.00    4111. 17.1     23.18    4958. 20.7
 257.   .00   .00  .00  1.432   28.93    3980. 16.6     25.27    4552. 19.0
 285.   .00   .00  .00  1.432   29.51    3904. 16.3     26.54    4335. 18.1
 356.   .00   .00  .00  1.432   30.94    3724. 15.5     29.65    3885. 16.2
 392.   .00   .00  .00  1.432   31.66    3641. 15.2     31.14    3701. 15.4
 437.   .00   .00  .00  1.432   32.55    3543. 14.8     32.02    3600. 15.0
 482(250C)    .00  .00  1.432   33.43    3451. 14.4     32.90    3506. 14.6
*  Design Condition
```

Note, however, that one drawback to the use of ACSS is the reduced safety factor under maximum ice load. The tension in Bittern ACSR reaches 38.5% of the rated breaking strength with 1 inch of radial ice at 32°F whereas it reaches 52.4% of the rated breaking strength of Bittern ACSS. Also, the cost of maintenance and the expected life of the new line with ACSS conductor must be evaluated relative to ACSR. ACSS has a reasonably long history of use (since 1970) and appears to yield maintenance costs and life expectancy that are roughly equivalent to ACSR though this cannot be confirmed until the conductor has been is use for a substantial period of time.

Connectors and Hardware

One of the primary and appropriate areas of concern with the use of HTLS conductors in both new lines and existing lines centers on the durability of connectors and hardware operating at conductor temperatures as high as 250°C. A surprising result of various laboratory tests performed for connectors and hardware developed for each of the HTLS conductors is that this does not seem to be an obvious short term problem. A recent presentation by Preformed Line Products included the following Figure 2.



Laboratory Testing

- Heat Profile (795 ARMOR-GRIP® Suspension

Figure 2 - Laboratory test tempertures for Armor Grip suspension with conductor at 210C (provided courtesy of Mr. Bob Whapham, PLP).

The key element in keeping the temperature of the elastomer and support system reasonably low is the presence of armor rods. Compression connectors for ACSS have undergone conventional 500 cycles tests successfully, but the long term survival of such fittings cycled repeatedly to conductor temperatures of 200°C and more is the present subject of research by EPRI and other utility organizations.

HTLS conductors can be used in new lines. The advantages of doing so, however, are less clear than for reconductoring existing lines. Certainly, on long lines which are unlikely to reach their conventional thermal capacity because of voltage drop or stability concerns, any advantages from the use of HTLS conductor is hard to identify.

In existing lines, there is a large advantage to using HTLS conductor in that the thermal rating of the line increased significantly without the expense and regulatory difficulties involved in rebuilding or replacing the existing structures. Therefore, the economic advantage associated with HTLS conductors in new lines is usually less than in reconductoring applications. In new lines, since the structures do not exist, a larger (i.e. lower resistance) conventional conductor can be used (see Figure 1) to yield a high thermal rating and stronger structures specified to handle the higher mechanical loads.

In terms of environmental effects – corona noise, audible noise, electric fields, magnetic fields - there are no advantages in using HTLS power conductors. In fact, at line voltages in excess of 230kV, there are some concerns that the loose aluminum strands utilized in ACSS and ACCC, may lead to a "rougher" conductor surface with higher corona noise problems. There are also concerns about conductor wear due to the use of spacers when these annealed strand HTLS conductors are used. Limited testing for a 345kV application of ACSS seems to indicate that these problems are minimal.

In terms of capital investment, one might argue that relatively small HTLS conductors could be used to build a new, short, thermally limited transmission lines at minimum cost. The line would have sufficient thermal capacity if operated at high temperatures while the cost of conductors and supporting structures would be low since the wind and ice loading is lower and the conductor weight per mile of line would also be low. This is probably true for short lines where the increased cost of electrical losses can be neglected and where the premium for HTLS conductor is modest.

ACSS and ACCC each use annealed aluminum strands which, after installation, have low tension levels. As a result, these conductors are likely to have high self-damping and can be installed at lower initial sags than standard ACSR. In addition, the sag under wind and ice loads for an ACSS/TW conductor purchased with an extra high strength steel core, the sag under ice load would also be less than standard ACSR and conductor motions due to ice dropping and ice galloping are likely to be less. This could be helpful in reducing phase to phase spacing and result in more compact structures. Correspondingly, the lower elastic modulus of the carbon fiber reinforced core of ACCC may not be sufficient to have a similar impact on new line design.

Available HTLS Designs

The essential advantage of reconductoring existing lines with HTLS conductors is that the line's thermal rating can be increased with minimal modification of existing transmission line structures. To limit the need for structural modification, these high temperature replacement conductors must operate at much higher temperature 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.

Desirable HTLS Conductor Characteristics

Clearly, HTLS conductors should have at least some of the following characteristics (relative to the original conductor):

- low thermal elongation rate (reduced rate of sag change with temperature)
- high mechanical self-damping (can be installed with less everyday sag)
- same or smaller outside diameter
- same or lower resistance

The replacement conductor mechanical characteristics which best avoid increasing the maximum structure tension loads while maintaining an acceptable level of safety under heavy loads are less clear. Also, while certain replacement conductor characteristics may be attractive, it is not obvious that such characteristics are "cost-effective" (i.e. that the additional cost of the special conductor is justified by the increase in line rating). Finally, the choice of HTLS replacement conductor is largely influenced by the existing conductor type and original line design conditions.

HTLS Component Materials

As with conventional ACSR, all of the HTLS conductor designs use aluminum strands to carry electrical current. The aluminum wire (1350-H0) used in ACSS and the ACCC conductor designs is electrically similar to conventional "full-hard" 1350-H19 "electrical conductor" grade aluminum but has much lower tensile strength since it is fully annealed (1350-H0).

The "zirconium" alloy of aluminum used in ACCR and in the various Japanese conductor designs such as G(Z)TACSR and (Z)TACIR is also very similar, both electrically and mechanically to 1350-H19 aluminum wire, but it may be operated at temperatures which would reduce the tensile strength of conventional aluminum. TA aluminum is widely used in Japan and has a continuous operating limit of 150°C. ZTA aluminum is much less commonly used but can be operated continuously at 200°C without any change in electrical or mechanical properties.

All HTLS conductors have a central reinforcing core to provide high tensile strength and to limit sag at high temperature. With ACSS and G(Z)TACSR, the reinforcing core is steel. With ACCR it is a ceramic fiber composite. With ACCC and ACFR it is a carbon-fiber reinforced resin.

HTLS Conductor Types

The advantages and disadvantages of each of the high temperature conductor designs are summarized in the following section. A comparison of their sag behavior as a function of operating temperature is also presented. The comparison is not exhaustive but rather presented in order to clarify the way in which each conductor combines material and construction innovations to allow operation at high temperature within the confines of adequate electrical clearance.

(Z)TACSR

(Z)TACSR has the same construction as conventional ACSR, with galvanized steel wires for the core and (Z)TAL wires (thermal-resistant aluminium alloy wires with zirconium added) surrounding them.

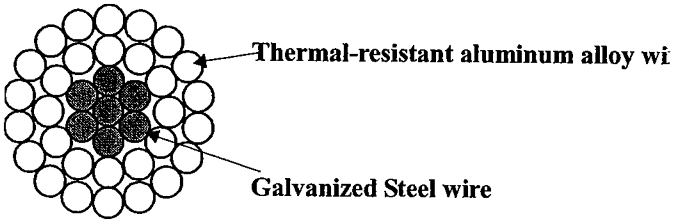


Figure 3 - Crossection of TACSR Conductor

(Z)TACSR conductor is, in almost all respects, identical to conventional ACSR conductors. The aluminium alloy used in (Z)TACSR has a slightly higher electrical resistivity than standard hard-drawn aluminium, but in all other respects the two conductors are almost identical. Unlike the conductors described below, (Z)TACSR is not, by design, a low-sag conductor. It has the same thermal elongation behavior as ACSR. The main advantage of (Z)TACSR is that its aluminium alloy wires do not anneal at temperatures up to 150°C for TAL and 210°C for ZTAL (Temperatures above 100°C would cause annealing of the aluminium strands in standard ACSR.

(Z)TACSR can therefore be used to uprate existing lines where some additional clearance is available. Steel-cored conductors (and other non-homogeneous conductors) have what is known as a "knee-point." This is a temperature above which the higher thermal expansion rate of aluminium causes all the stress of the conductor to be borne by the steel core. Beyond this knee-point temperature, therefore, the conductor experiences a sag increase due to the expansion of steel alone. This new expansion coefficient will be lower than that for the conductor at lower temperatures, resulting in relatively low sag increases when operated at high temperature. Standard ACSR exhibits this property, but usually at a temperature beyond the annealing limit. The TAL alloy of TACSR allows this behavior to be exploited. At present TACSR is currently used in place of conventional ACSR in many transmission lines in Japan.

G(Z)TACSR

Gap-type conductor has a unique construction. There is small gap between steel core and innermost shaped aluminium layer, in order to allow the conductor to be tensioned on the steel core only. 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. The gap is filled with heat-resistant grease (filler), to reduce friction between steel core and aluminium layer, and to prevent water penetration.

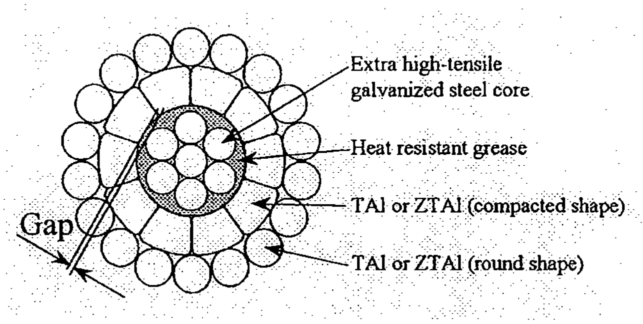


Figure 4 - Cross-section of GTACSR conductor

During installation of G(Z)TACSR, the aluminium 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 aluminium layers are re-stranded and trimmed, and aluminium body of the dead-end clamp compressed. Although this special erection technique is different from that employed with conductors of standard construction, the compression splices and bolted suspension clamps are similar. In addition, in order to assure proper performance of this conductor, a special type of suspension clamp hardware must be installed every three suspension spans.

There is limited field experience. National Grid successfully installed a 2 km length of GTACSR in a 400 kV line in England. 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.

(Z)TACIR

As with (Z)TACSR, (Z)TACIR has a conventional stranded construction (identical to ACSR), making use of material innovations to give properties allowing the conductor to be operated at high temperatures. In place of the steel strands of (Z)TACSR, it has galvanized or aluminium-clad invar alloy steel wires for the core and (Z)TAL wires surrounding them. ZTAL resists annealing up to a continuous temperature of 200°C.

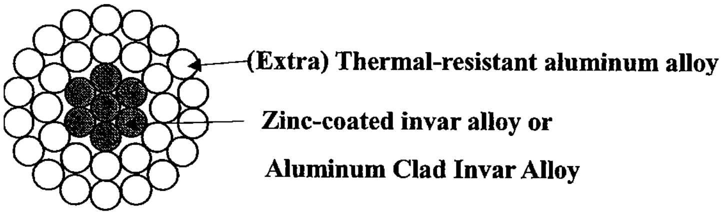


Figure 5 - Cross-section of (Z)TACIR conductor.

Invar is an iron-nickel alloy (Fe—36%Ni) with a very small coefficient of thermal expansion. The coefficient of thermal expansion of invar wire is around one third that of galvanized or aluminium-clad steel wire.

The installation methods and accessories for the conductor are virtually the same as those used for conventional ACSR. A slight lengthening of compression type accessories is required only to satisfy increased current carrying requirements.

ACSS and ACSS/TW (Originally designated SSAC)

Aluminium Conductor Steel Supported (ACSS) and Shaped (Trapezoidal)-Wire Aluminium Conductor Steel Supported (ACSS/TW) are specified by ASTM standards. For both, the aluminum strands are fully annealed (1350-0) concentric-lay-stranded about a multi-strand steel core. Annealed aluminum also has a somewhat higher conductivity than 1350-H19 aluminum (63% versus 61.2%). ACSS is not available in conductors with a single strand steel core.

The coated steel core wires may either be aluminized, galvanized, zinc-5%aluminium Mischmetal coated or aluminium clad. The steel core is available with either high strength or extra high strength steel. The "extra high strength" steel has a tensile strength about 10% greater than high strength steel core wire. In appearance, ACSS conductors are essentially identical to standard ACSR conductors. There are three different designs:

- "Standard Round Strand ACSS"
- "Trapezoidal Aluminium Wire ACSS/TW" with equal area
- "Trapezoidal Aluminium Wire ACSS/TW" with equal diameter to conventional round wire constructions.

For example, the ACSS replacements for Bittern ACSR are: Bittern ACSS (same diameter and nearly the same resistance as Bittern ACSR); Bittern ACSS/TW (reduced diameter and nearly the same resistance as Bittern ACSR) and: Potomac ACSS/TW (same diameter and lower resistance than Bittern ACSR. Potomac ACSS/TW has about 20% more aluminum and therefore costs more than the other two. Special high strength constructions are also available.

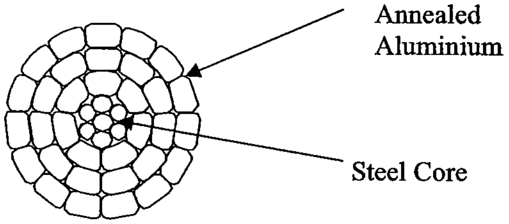


Figure 6 - Cross-section of ACSS/TW conductor.

In all designs, the use of annealed aluminium strands yields much higher mechanical self-damping than standard ACSR of the same stranding ratio.

Because the tensile strength of annealed aluminium is lower than 1350-H19, the rated strength of ACSS is reduced by an amount dependent on the stranding (e.g. 35% for 45/7, 18% for 26/7, 10% for 30/7) compared to similar constructions of ACSR. In fact, a 45/7 ACSS conductor, with standard strength steel core wire has about the same rated breaking strength as a conventional all aluminium conductors made with hard drawn aluminium wire. The reduced strength of ACSS can be offset by using extra-high strength steel core wires, by using a higher steel core area, or by doing both.

Since the tension in the annealed aluminium wires is so low, the thermal elongation of ACSS is essentially that of the steel core alone. Similarly, given the low tension in the aluminium strands, ACSS does not creep under everyday tension loading. ACSS/TW constructions behave in the same manner as ACSS but have the added advantages of reduced ice and wind loading and reduced wind drag per unit aluminium area.

ACCR and ACCR/TW

The core of ACCR is made of ceramic fibers embedded in an aluminum matrix. The surrounding aluminum strands are Japanese ZTAL, usually trapezoidal. This conductor is commercially available in limited quantities from the 3M Company.

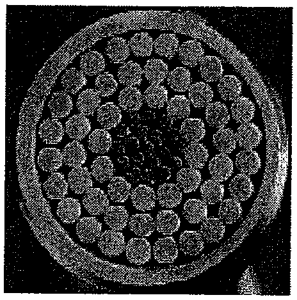


Figure 7 - Crossection of ACCR conductor.

The thermal elongation rate of the composite core material is about half that of steel and when combined with the ZTAL aluminum the conductor is strong enough for use in any loading environment. Extensive tests have been performed on several sizes (477, 795, and 1272 kcmil) of this conductor under laboratory conditions. Specific terminations and suspension clamps have been developed by Alcoa and Preformed Line Products.

Xcel Energy successfully completed a field test, with a single 800 ft span, in Minneapolis. Other field tests are underway in North Dakota (1 mile of 230kV line), at Hawaiian Electric (three spans near the sea), and recently at Salt River Project in Arizona. 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.

Under a DOE project, a two span test line has been set up with ACCR for an extended period of high temperature testing. 3M has invested considerable engineering effort in studying the details of conductor and accessory behavior under realistic high temperature conditions.

Practically speaking, reconductoring existing lines with this conductor will usually produce somewhat higher thermal ratings than reconductoring with ACSS, perhaps 10% more, but the cost of ACCR appears to be more than 10 times the cost of ACSS. The price makes this conductor suitable for those uprating niches where other conductors will not work. It is not necessary to pay so much in most uprating applications.

ACFR (Showa Electric)

The core of this conductor is made of carbon fibers embedded in resin. The surrounding [illegible] zirconium alloy, TAL, or ordinary 1350-H19 aluminum. The manufacturer claims a continuous operating temperature of 150°C for the first and 100°C for the latter. 150°C seems to be the maximum allowable temperature due to concerns about the long term deterioration of the carbon-reinforced resin core.

The conductor, its laboratory testing, and a limited field test in Northern Japan was described in CIGRE paper 22-203 presented in Paris in august, 2002. In that paper the core characteristics are described. The core thermal

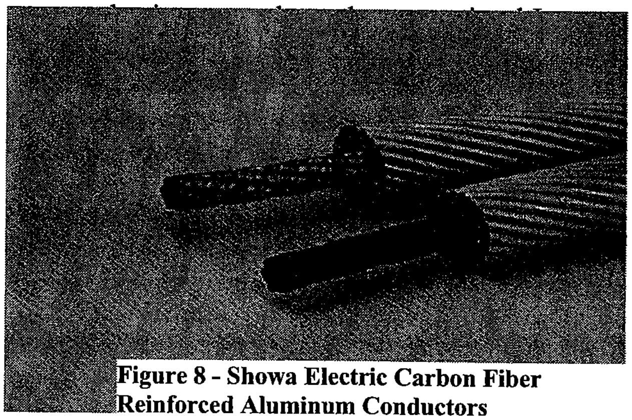


Figure 8 - Showa Electric Carbon Fiber Reinforced Aluminum Conductors

elongation is approximately 10% that of steel so that above the knee-point temperature, the sag change is negligible. On the other hand, the modulus of the carbon fiber reinforced resin is only about 2/3 that of steel. The weight of the complete conductor is 30% that of ACSR.

Major question remain regarding the long term corrosion problem between aluminum and the carbon fibers as well as the service life of the resin. Certainly, there have been many complex service life issues with composite insulators. The conductor has been manufactured and field tested after extensive laboratory tests. Accessories are available.

ACCC/TW (CTC)

This company originally proposed the production of CRAC conductor with a simple fiberglass core. More recently, they have proposed and performed limited laboratory testing on this ACCC conductor that consists of annealed trapezoidal aluminum strands surrounding a carbon-reinforced resin core. Based on my review of their initial tests, I assumed that the core material is very similar to that reported by Showa Electric in their CIGRE paper.

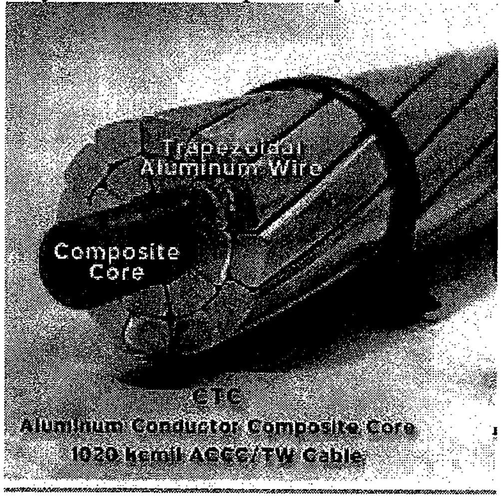


Figure 9 - CTC ACCC Conductor with Carbon fiber Reinforced Resin Core

As noted in the discussion of ACFR above, the modulus of the carbon-reinforced resin is only about 2/3 that of steel. When surrounded by annealed aluminum strands, the complete conductor is much weaker than ACSR and even weaker than ACSS. As can be seen in some of first test case evaluation in this report, this low stiffness translates into a relatively large sag under heavy ice loads. Combined with the low thermal elongation rate of the resin core, the sag of the conductor under ice loading appears likely to greatly exceed the sag at high temperature.

The conductor has been made by General Cable in reel lengths but laboratory tests performed by Kinectrics (Ontario Hydro) are limited to a single length. There have been limited tests of splices and dead-ends which indicate success in using conventional compression hardware.

Practical concerns with newly developed conductors.

Although this document is primarily a technical analysis concerning the application of of HTLS conductors, it is essential to include the practical concerns that often dictates whether new products such as the HTLS conductors are used or not.

Economics of HTLS conductor

There are two primary economic issues that influence the acceptance or rejection of HTLS conductors in both new lines and in uprating existing lines. The first factor is any "premium" charged by the manufacturer for their HTLS conductor relative to the cost of a similar ACSR conductor. The second concerns availability from multiple manufacturers which allows competitive bidding on large purchases. The two economic factors may be related.

Among the various HTLS conductor types, ACSS is available for a relatively small cost premium over regular ACSR and it is presently available in North America from three different manufacturers. None of the other HTLS conductor types is available from multiple manufacturers.

The cost premium of HTLS conductors has little to do with their stranding and much to do with their constituent wire materials. The Japanese "heat-resistant (TAL) and "super heat-resistant (ZTAL)" zirconium alloys of aluminum cost about 3 times as much as standard 1350 aluminum wires. Any HTLS conductor which uses these special alloys of aluminum can be expected to carry large cost premium. Similarly, the cost of "INVAR" steel is at least 3 times that of regular galvanized steel wire. Thus it appears certain that G(Z)TACSR will cost at least 2 to 3 times as much as ACSR and (Z)TACIR will be more than 3 times as expensive.

The 3M ACCR conductor core (ceramic fibers in an aluminum matrix) is apparently more than 10 times as expensive as ordinary steel. Since this conductor also uses the ZTAL aluminum alloy, it will cost about 10 times as much as ordinary ACSR depending on the actual amount of core required.

The original Goldsworthy CRAC conductor and the more recent version under development by Glasform appears to be relatively inexpensive. Fiberglas should be comparable to steel and surrounded by annealed aluminum, the CRAC conductor should be no more expensive than standard ACSR. Of course, it may not have sufficiently good mechanical properties to be practical.

Both the CTC and the Showa Electric conductors utilize a core consisting of carbon filaments embedded in a high temperature resin. The cost of this material is difficult to assess since it is still under development. Nonetheless, it appears that the core material is unlikely to cost less than 3 times as much as steel. In the CTC design, annealed aluminum is used and the total cost premium with the carbon fiber reinforced core should be in the range of 2 to 3 relative to ACSR. In the Showa Electric design, ZTAL is used and the cost premium is probably about 3 to 5.

Previous "new" conductor problems

Most of us have grown up with the idea that new technologies are constantly being developed in order to solve technical problems. We expect a "cure" for cancer, a "solution" for excessive low mileage in cars that weight 6000 lbs. In the area of transmission lines, new technologies have become available. We are able to support lines with structures that are simpler to install and are cheaper to maintain. In the area of conductors, the goal is to find designs and materials that reduce line cost and allow reduced esthetic and environmental impact. To these ends, a number of conductors have "emerged" in the last 50 years. These include "self-damping" conductor (SDC), twisted pair (T2) conductors, and aluminum conductor reinforced with a core of high strength aluminum alloy rather than steel. Also, we draw aluminum strands from "continuous cast" rod rather than traditional "rolled" aluminum rod.

Unfortunately, using bare stranded conductors in overhead power transmission lines is an extremely demanding application. The lines are designed for an economic life of 40 years but most of the lines in the United States are older than this. The conductors are subject to severe winds (hurricanes in Florida, tornados in the mid-west), severe ice buildup on all conductors that can persist for days or even weeks (especially in the northern US and Canada), to small magnitude and large magnitude wind-induced motions that can cause strand fatigue and repeated flashovers, and to sudden increases in electrical power flow (attempting to maintain service during system disruptions) that can drive the conductor temperature from 70°F to 400°F in a few minutes. Rainfall and condensation, especially near seawater, can allow corrosion between different metals such as steel and aluminum. On the other hand, utilities must above all protect the public safety by maintaining minimum clearances between energized conductors and people, vehicles, and other conductors in lower voltage power lines and communication circuits.

Severe requirements for HTLS conductors

HTLS conductors will undoubtedly see more severe operating conditions than normal ACSR since the current levels will be higher and both cyclic temperature ranges and occasional emergency temperature excursions are much higher than for ordinary ACSR.

Necessary laboratory and field tests

Steps in transmission conductor commercialization include the following:
Initial manufacture of wires with consistent electrical and mechanical properties including the following:

- % elongation at tensile break
- stress at break
- stress at yield point
- Demonstrate ability to strand core and or outer layers from wires
- Measurement of corrosion rates.
- Measurement of wire fatigue and mechanical self-damping properties
- Measure long-time plastic elongation rates of stranded conductor.
- Measure stress-strain properties.
- Perform field tests to provide tension stringing and sagging guidance
- Demonstrate successful attachments and connectors for conductor.
- Establish sagging block and bull wheel dimensions for installation.

Which HTLS conductors can be defined as "commercially available"

Among the HTLS conductors that are said to be commercially available, only the 3M ACCR, the J-Power GTACSR and TACIR, and the ACSS conductors have been thoroughly tested in the laboratory and in the field.

The CTC ACCC conductor has been tested in a single stress-strain and creep elongation test. No published data is available for this conductor.

Overhead transmission lines must be very conservatively designed and built such that the public is not injured by contact with the 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, dimensional checks on component wires, as well as stringing and sagging instructions, for review by the transmission line owner. The varying stages of development for HTLS conductors is illustrated in Table 4:

Table 4 - 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]	No
(T)ACFR(Showa)	Yes	No	[5]	No
ACCC(CTC)	Preliminary	Preliminary	[6]	No

[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 (3 years), six spans at HECO (2 years), 1 mile of 230kV at WAPA (2 years), Oakridge DOE tests, two new 2-span field tests in AZ.
[5] – Single span of each type (90C and 150C) exposed to severe ice and wind conditions in northern Japan.
[6] – 21 mile line in Kansas to be built in 2004.

HTLS Comparison in Reconductoring Clearance-Limited Lines

The basic advantage of reconductoring an existing transmission line with HTLS conductor is its ability to operate at higher temperatures than conventional ACSR without losing strength or failing. As the name implies, a secondary advantage of HTLS conductors is that they sag less at temperatures above 100°C.

In the following examples, an existing line is to be reconductored with HTLS conductor. The clearance margin varies between the examples. In each example, the increase in thermal rating due to reconductoring with various types of HTLS is estimated.

It is clear that HTLS conductors, whatever the type, are effective in increasing the thermal rating of clearance limited overhead lines. It is also clear that the most effective type of HTLS conductor varies with the particular design conditions.

HTLS Comparison – Example #1

In this example, the original conductor is 795 kcmil 26/7 Drake ACSR and the ruling span length is 900 ft. The line was originally designed to meet NESC ground clearance requirements at 140°C with a sag of 30 ft. The summary of design conditions is:

- Drake 795 kcmil ACSR original conductor
- NESC Hvy (no high ice) loading
- 35% RBS at 0°C, NESC Heavy load
- 900 ft ruling span

In order to avoid extensive structure modifications, the HTLS conductors are selected to have the same diameter as the original Drake ACSR and a maximum tension which is less than or equal to that of the original (0.35 * 31,500 = 11,025 lbs).

The initial unloaded sags of the HTLS replacement conductors can be less than that of Drake ACSR if they have higher self-damping and are thus less prone to vibration fatigue failures. ACSS and ACCC employ annealed aluminum strands and, as a result, exhibit higher self-damping than ACSR or ACCR.

Finally, the sag of the HTLS conductors under NESC Heavy loading conditions must also be less than the 30 ft sag limit.

Meeting sag clearance limits with HTLS Conductors

Figure 10 illustrates a comparison of sag behavior for the original Drake ACSR and three HTLS conductors. From this figure it can be seen that:

- All HTLS conductors meet the 30 ft sag limit at 200°C (392°F) but the sag of ACSS is the largest since it's core is ordinary steel with the highest CTE coefficient.
- All HTLS conductors meet the sag limit under maximum ice and wind load but the sag change for ACCC is highest since it has the lowest stiffness.

- Both ACCR (3M) and ACCC (CTC) could be operated above 200°C (392°F) with less than 30 ft of sag.
- All three HTLS conductors can be operated to their manufacturer's maximum recommended continuous temperature while meeting the sag clearance limit for the line.
- Using NU/UI rating weather assumptions, at 200°C, since the three HTLS conductors have about the same resistance and diameter, the thermal rating of each is similar at approximately 1850 amperes. The original Drake ACSR at 100°C has a rating of approximately 1200 amperes. The use of HTLS conductor results in a 50% increase in the continuous thermal rating of the existing line.

Since the three HTLS conductors all yield about the same thermal rating increase, the choice of HTLS replacement conductor depends on the cost and the probable service life of each. The round strand HTLS conductors considered in this example could be replaced by TW versions of each to get a higher rating.

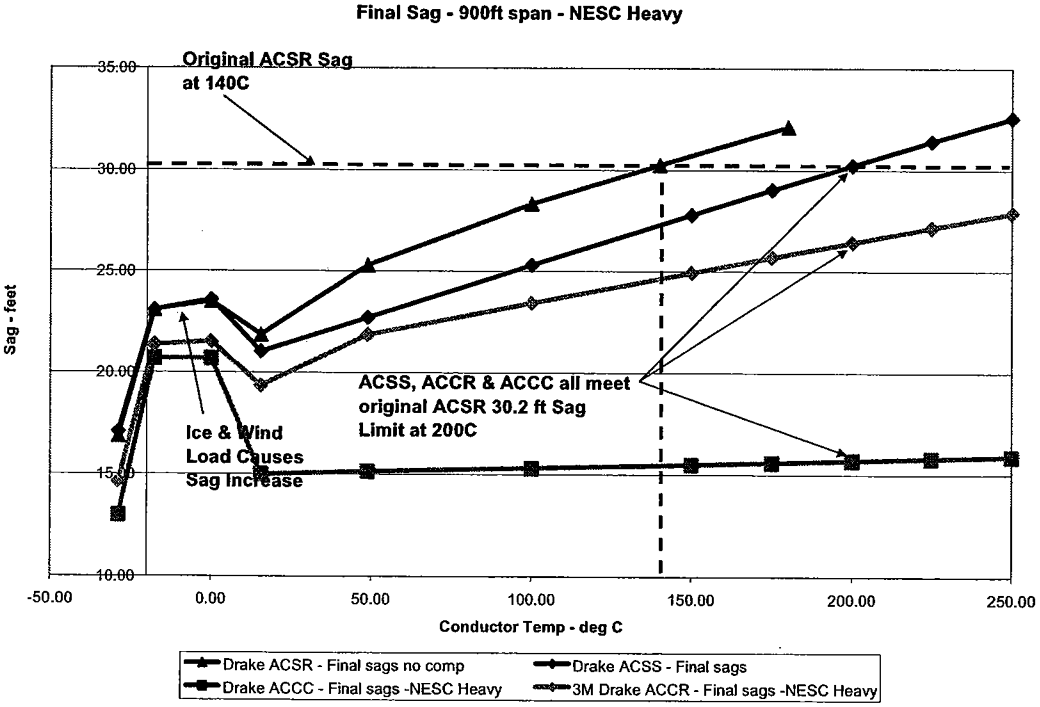


Figure 10 - Sag versus Conductor Temperature for Drake ACSR and HTLS Replacement Conductors for Example #1.

HTLS Comparison – Example #2.

This case study is excerpted from the recent CIGRE technical brochure 244 developed by Working Group B2.12. The author of this report is the convenor of that working group and was a primary author of the brochure.

In this case study, the original line clearance buffer is assumed to be approximately 3 ft. The maximum final sag of the original Bear ACSR conductor at its maximum allowable temperature of 100°C is 6.65 m(21.8 ft). This can be increased to 7.65m (25.1 ft) with the replacement conductor. The rating of Bear ACSR at 100°C is 815 amperes.

The maximum conductor tension of the original Bear ACSR is 53.7% of its RBS. The maximum tension of the original design with the relatively strong Bear ACSR is 62307 N so the replacement conductor maximum tension may not exceed 68 540 N (10% higher). The diameter of the replacement conductor must not exceed 24.7 mm.

```
                 ALUMINIUM COMPANY OF AMERICA SAG AND TENSION DATA

                   Case 3 - Heavy loading, 30/7 264.4mm2 ACSR Bear
                              Max Sag with 1 meter buffer

Conductor BEAR              ACSR/British

Area=  326.5800 mm^2    Dia=23.470 mm    Wt=11.952 N/m    RTS=  116099 N

Span=      275.0 m

    Design Points                           Final                     Initial
 Temp    Ice    Wind    K    Weight    Sag  Tension   RTS       Sag  Tension   RTS
   C      mm   N/m^2   N/m    N/m       m      N       %         m      N       %
 -20.  25.00      .0   .00  46.051    7.01   62307.  53.7       7.01   62307.  53.7
 -20.  12.50   190.0   .00  26.271    5.49   45309.  39.0       5.08   48929.  42.1
 -30.    .00      .0   .00  11.952    3.41   33203.  28.6       2.79   40491.  34.9
  16.    .00      .0   .00  11.952    4.87   23220.  20.0*      3.73   30338.  26.1
  50.    .00      .0   .00  11.952    5.82   19449.  16.8       4.63   24439.  21.0
  75.    .00      .0   .00  11.952    6.24   18163.  15.6       5.35   21151.  18.2
 100.    .00      .0   .00  11.952    6.65   17030.  14.7       6.08   18623.  16.0
*  Design Condition
```

Table 5 - Reconductoring Calculations for Example #2.

Conductor	ACSR	GZTACSR	TACIR	ACSS/TW
Name	Bear	260	260	400 (Scoter/TW)
Total Area (mm^2)	326.6	317.6	326.6	397.4
Alum Area (mm^2)	264.4	261.3	264.4	Area
Outside Diameter (mm)	23.5	22.6 (-0.4%)	23.5 (0%)	24.2 (3%)
Rated Tensile Strength (kN)	116.1	123.5 (+3.4%)	98.5 (-15.2%)	132.1 (+14%)
Tension @Max Load (kN)	62.3	62.3	49.3 (-21%)	67.8 (+8.8%)
DC Resistance @ 25°C(μΩ/m)	109.3	115.3 (+3.4%)	113.3 (+1.6%)	89.8 (-18%)
Conductor mass per unit length (kg/m)	1.219	1.188 (-2.3%)	1.227 (+0.7%)	1.48 (+22%)
H/w @16C (m)	1943	1512	1250	2237
Cont. Operation Max. Temp (°C)	100	210	65	100
Rating (amps) *	815 @100°C	1230 @190°C	705 @85°C	1490 @200°C

* - Conductor temperature limit due to both sag and manufacturer's continuous recommendation.

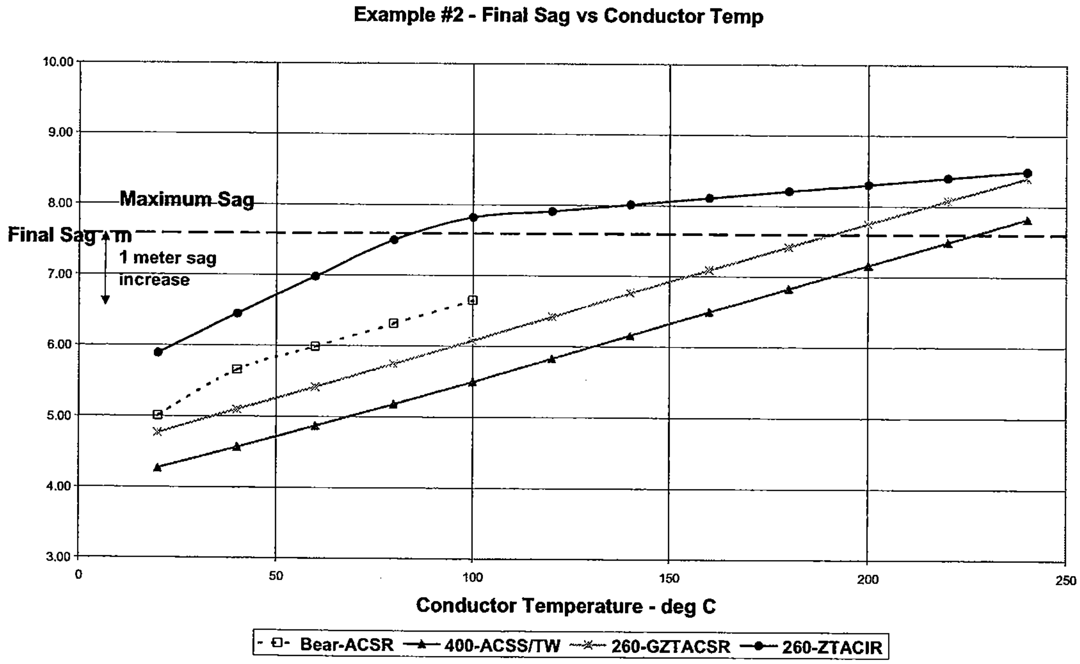


Figure 11 - Sag Variation with Temperature for Original Bear ACSR and ACSS, ACSS/TW, ZTACIR, and GZTACSR Replacement Conductors in Example #2.

HTLS conductor Comparison – Example #3

The ruling span for example #3 is 350 m (1150 ft), the maximum final unloaded sag of the original ACSR conductor at the design temperature of 75°C is 11.4m (37.4 ft). The rating of the original 54/7 Zebra ACSR at 75°C is 805 amperes. Given that the original maximum sag can be increased by 1 m (3 ft), the sag of the replacement conductor may not exceed 12.4m (40.7 ft).

- The original conductor is Zebra ACSR.
- The ruling (i.e."effective") span length is 350 meters (1150 ft).
- The original conductor tension limits are 20% RBS unloaded final at 16°C (everyday limit) and 60% RBS under maximum loading conditions.
- The maximum loading condition is 6.25 mm ice and 190 Pa wind at 10°C.
- The sag "buffer" (or "excess" clearance) at the Zebra ACSR maximum operating temperature of 75°C is 1 meter.

To avoid extensive reconstruction of the existing line structures, the application of replacement conductor is limited as follows:

- The outside diameter of the replacement HTLS conductor can be no more than 5% greater than Zebra.
- The maximum replacement conductor tension under ice and wind loading cannot be more than 10% greater than the original maximum tension.
- The final unloaded sag of the replacement conductor at its maximum allowable conductor temperature cannot exceed the original maximum conductor sag by more than the sag buffer – 1 meter.

The original maximum conductor tension is 42695 N (9,600 lbs). The maximum tension of each of the replacement HTLS conductors is limited to this tension plus 10% or 46965 N (10,560 lbs). The diameter of the original Zebra ACSR is 28.575mm so the outside diameter of the replacement conductor cannot exceed 30.00mm (5% greater).

The line rating is calculated for all conductors on the basis of a 0.61 m/s wind perpendicular to the conductor, air temperature 35°C, solar heating for 35 degrees north latitude at noon in summer, emissivity = 0.7, absorptivity = 0.9.

The manufacturer's recommendations for continuous operation is 210°C for the ZTAL in GZTACSR and ZTICR, 200°C for annealed aluminum in ACSS and ACSS/TW conductors with heat resistant steel wire coatings, and 150°C for TAL in GTACSR and TACIR.

The original conductor sag-tension design calculations are described in the following. Note that the calculations consider permanent elongation due to high-tension events and everyday creep at 15°C for 10 years. The "final" values shown include this elongation. Ice is assumed to be glaze ice with a density of 1600 kg per m3. The stress-strain data is derived from experimental curves.

Line Uprating Case Study - Original Conductor Zebra ACSR and Moderate Ice and Wind Loading

ALUMINUM COMPANY OF AMERICA SAG AND TENSION DATA

Medium loading, 54/7 489mm2 (Zebra) ACSR
1 meters "excess" sag

Conductor ZEBRA ACSR/British

Area= 482.9023 Sq. mm Dia=28.575 mm Wt=15.878 N/m RTS= 133002 N

Span= 350.0 m

Design Points					Final			Initial		
Temp C	Ice mm	Wind N/m^2	K N/m	Weight N/m	Sag m	Tension N	RTS %	Sag m	Tension N	RTS %
-10.	6.25	190.0	.00	23.346	8.97	39983.	30.1	8.40	42695.	32.1
-18.	.00	.0	.00	15.878	7.80	31265.	23.5	6.94	35116.	26.4
16.	.00	.0	.00	15.878	9.17	26600.	20.0*	8.13	29996.	22.6
50.	.00	.0	.00	15.878	10.47	23338.	17.5	9.34	26130.	19.6
75.	.00	.0	.00	15.878	$\boxed{11.36}$	21518.	16.2	10.21	23911.	18.0
100.	.00	.0	.00	15.878	12.21	20038.	15.1	11.06	22094.	16.6

*** Design Condition**

Given the sag limit of 12.4 meters (11.4 + 1 m), only the GZTACSR replacement conductor is able to operate at its maximum continuous temperature limit (210°C). The maximum operating temperature of all the other replacement conductors is determined by sag.

The Suwanee ACSS/TW conductor can be operated to 165°C at which temperature the sag limit is reached. The TACIR conductor can only reach 85°C, however, for which its thermal rating is less than the original Bear conductor.

Note the relatively low knee point temperature for the ACSS/TW and TACIR conductors due to the heavy loading conditions that cause a relatively large amount of permanent elongation in the aluminium strands.

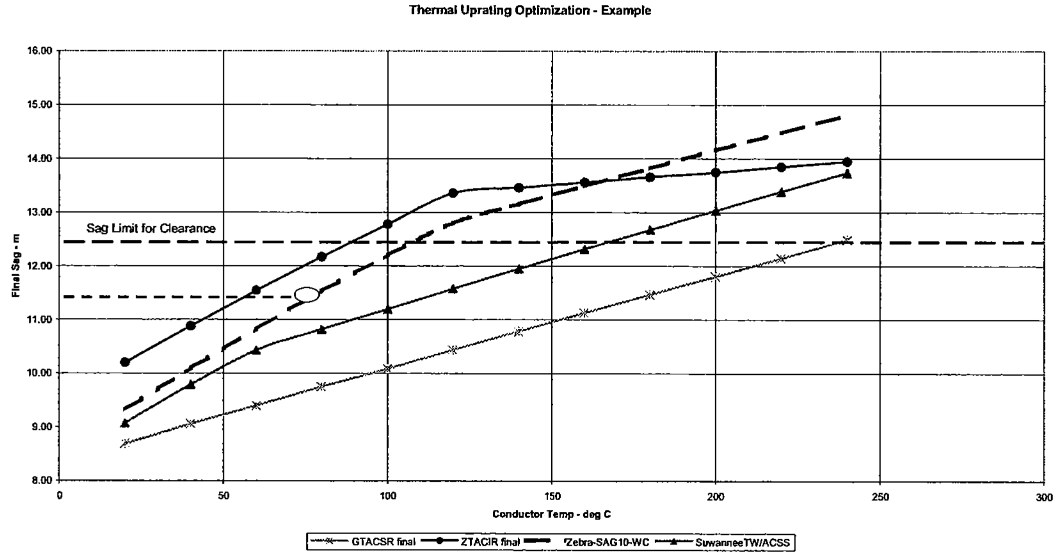


Figure 12 - Sag Variation with Temperature for Original Zebra ACSR and for possible ACSS/TW, TACIR, and GZTACSR Replacement Conductors.

The everyday sag of GZTACSR is less than the original Bear ACSR (reflecting the higher self-damping of this gapped conductor design) and the everyday sag of the TACIR is greater (reflecting the lower tensile strength of its Invar steel core). The ACSS/TW conductor has the lowest everyday sag of all because of its inherent high self-damping and modest stiffness. The sag of the ACSS/TW replacement conductor is determined by limiting the initial unloaded tension at 16°C to 35% of RTS.

Reconductoring Calculations for Line Uprating Case Study

Table 6 - Characteristics and Thermal Ratings of Replacement Conductors for Case Study

Conductor	ACSR	GZTACSR	TACIR	ACSS/TW
Name	Zebra	440	430	Suwannee
Total Area (mm^2)	484.5	491.9	484.5	565.3
Alum Area (mm2)	428.9	439.1	428.9	486.3
OD (mm)	28.62	28.5 (-0.4)	28.62 (0%)	28.1 (-1.9%)
Rated Tensile Strength (kN)	131.9	146.8 (+11.3%)	121.9 (-7.6%)	147.2
%RTS at Max Load	30.6	30.0	30.1	32.0
DC Resistance @ 25°C (μΩ/m)	68.7	70.0 (+1.9%)	69.9 (+1.7%)	58.6 (-15%)
Conductor Weight (kg/m)	1.621	1.658 (-2.3%)	1.633 (+0.7%)	1.960 (+20.9%)
Final H/w at 16C(m)	1659	1797	1522	1720
Cont. Operation Max. Temp (°C)	100	210	210	200
Rating (amps) *	805 @75C	1890 @210C	990 @90C	1685 @165C

* - Conductor temperature limit due to both sag and manufacturer's continuous recommendation.

The final sag estimate for the original Zebra ACSR as a function of conductor temperature shows that the original conductor could be operated at a temperature higher than 75°C without exceeding the clearance limit on sag. At 100°C, the original Zebra ACSR has a thermal rating of 1050 amperes, an increase of 30% over the existing line rating.

The GZTACSR replacement conductor can be operated at its maximum recommended continuous operating temperature (210°C) without exceeding the sag limit of 12.4 meters. The corresponding line rating is 1890 amperes, which is 135% over the original rating. Notice that the gapped conductor is installed with less everyday sag than the original Zebra reflecting its higher self-damping.

The TACIR replacement conductor (capable of continuous operation at 150°C) is limited to operation at 90°C where it's rating would be only 23% above the existing rating. TACIR would yield a much higher rating if it could be installed with less everyday sag but this is limited by the Invar core's lower tensile strength.

As with GZTACSR, the everyday sag of Suwannee ACSS/TW can be less than the original Zebra ACSR because of its higher self-damping. This replacement conductor can be operated up to 165°C without exceeding the 12.4 m sag limit. This yields a thermal line rating of 1685 amps that is 110% higher than the existing line.

As in most line uprating studies, the system requirements may determine the uprating method. If only a small increase in the thermal rating is required, then the 30% increase in rating obtained by simply operating the existing Zebra ACSR at 100°C may be sufficient. This is certainly the least expensive solution. If a large increase in the thermal rating is required then either ACSS/TW or GZTACSR replacement conductors can be used without needing to rebuild the line structures. Each gives an increase of line rating in excess of 100%.

The choice between ACSS/TW and GZTACSR is likely to depend on differences in construction methods and product cost since both yield an adequately large increase in line thermal rating.

Conclusions

There are many sorts of power flow limitation in modern power systems. If the problem can be solved by a relatively large increase in the thermal rating of an overhead line, reconductoring the line with HTLS conductor is a possible solution. These conductors are capable of high temperature operation with minimal change in electrical and mechanical properties and they sag less at high temperatures than conventional ACSR conductors.

How HTLS Conductors Work.

In existing lines, replacing the ordinary ACSR conductors with an HTLS conductor can typically increase the rating of the line by at least 30% and as much as 100% over present NU/UI line ratings with ACSR.

HTLS conductors work by maintaining stable physical and electrical properties even after exposure to operating temperatures as high as 250°C and sagging less than standard conductors at these high temperatures.

In new lines, the advantage of using HTLS conductors is less certain. Any HTLS conductor cost premium over standard conductor and the cost of electrical losses are important factors in determining whether HTLKS conductors should be used in new lines.

Exercise caution with new conductor designs.

HTLS conductors and associated connectors and hardware will be subject to much higher operating temperatures than ACSR. Historically, certain problems associated with the introduction of new types of transmission conductor have only been discovered after extensive utilization and years of exposure to the relatively harsh environment carrying widely varying levels of power.

Certain of the HTLS conductors have been thoroughly tested. These include ACSS, G(Z)TACSR, ACCR (3M) and (Z)TACIR. All have been extensively tested in laboratories and have been studied in multiple field tests. Only ACSS has been commercially available for a long period of time (30 years) and used successfully in hundreds of line uprating applications.

HTLS Conductor for Uprating Existing Lines

All of the HTLS conductors increase line rating by operating at higher maximum temperatures than ACSR and by sagging less at high temperature. Any detailed technical comparison leads to the conclusion that no one HTLS conductor is superior in every application. In a general sense, they all work well enough, though one design may give higher ratings in a particular application.

On the basis of manufacturer's laboratory and field testing, ACSS, GTACSR, and ACCR(3M) seem to be proven conductor products. The other HTLS conductors are in various states of development.

ACSS is unique in that it has been used extensively in North America, has been sold commercially over a 30 year period, is presently available commercially from three different suppliers, can be ordered to ASTM specifications, and commands a very modest cost premium.

It appears that ACSS or ACSS/TW are the most attractive choices both for use in uprating existing lines and for application to new lines which require high thermal ratings.

HTLS Conductors for New Lines

The case for using HTLS conductors in new lines, particularly new EHV lines, is less compelling than for Uprating existing lines. Nonetheless, for short lines subject to high post-contingency emergency power flows, the use of HTLS conductors, particularly ACSS, may be worth considering.

For longer lines where power flow is limited by voltage drop or stability concerns there is no reason at all to consider the use of HTLS conductors.

Given the modest cost premium, the high self-damping and relatively low peak tension loads typical of ACSS, this HTLS conductor is probably the most attractive HTLS conductor for use in new lines.

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Appendix I – Wire Materials for ACSR and HTLS Conductors?

Table 7 lists material properties for normal "electrical conductor" grade (1350) full hard-drawn (H19) aluminum wires and "A Class" galvanized, high strength steel wires which are used in standard ACSR conductors. Note that the tensile strength of the steel core wires is approximately 7.5 times and the stiffness (modulus) is approximately 3.5 times that of 1350-H19 aluminum.

None of the HTLS conductors use 1350-H19 aluminum since this material loses tensile strength at temperatures above 90°C. Certain HTLS conductor do, however, use galvanized steel core wires since it is inexpensive and unaffected by temperatures below 300°C.

Aluminum alloys and tempers

Above 100°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 20% instead of 1%. Its tensile strength is unaffected by exposure to high temperatures. Annealed aluminum wires are attractive for use in HTLS conductors since it can be operated to 300C without any change in its properties.

TAL and ZTAL are Zirconium aluminum alloys that can be operated continuously at temperatures of up to 150°C and 210°C, respectively, without loss of tensile strength.

Reinforcing core materials

Aweld is Alumoweld that 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" coated steel wires are capable of operation to 350C.

Invar steel alloy wires 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 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.

Graphite carbon fibers can be embedded in a resin to make a reinforcing core material. Many variations in resin are possible but clearly the use of any plastic material in transmission conductors intended for use at high temperature must be carefully tested in realistic conditions.

Table 7 - Conductor 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	2.7	60
ZTAL	210	1	7/24	23	2.7	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	2.7	10 to 30
Experimental Reinforcing Wire Materials						
Thermoplastic Composite (Glasform/Goldsworthyy)	<150	3	7/200	~ 6	1.5	0
CFCC (Showa Elec)	90C & 150C	1.5	20/530	1.0	1.6	0
Fiberglas/carbon (CTC)	>200C?	2.0	18/	~1.0	1.6	0
Graphite fibers* (generic)	250	~ 1	33/360	~ -1.	1.8	0

Appendix II - Questions & Answers on HTLS Conductors

What advantage is there to the use of trapezoidal aluminum strands?

With trapezoidal aluminum strands, the conductor resistance is approximately 25% lower than for round strands with the same overall conductor diameter. In general, any of the HTLS conductors can be manufactured with trapezoidal aluminum strands in which case the cost per unit length is higher and the thermal rating is increased by about 10%.

What materials are used in transmission lines?

Transmission Line structures are usually made of steel (pole or lattice) or wood (single pole or H-Frame). Structure foundations are made of concrete, steel, or a combination of the two. Conductors are made of steel (lightning shield wires), aluminum (power conductors), or a combination of the two. Insulators are made of ceramic, glass, or plastic composites. The cost per pound of these various materials is modest. The low cost of materials is one of the reasons that overhead lines are 3 to 10 times cheaper to build than underground cables with the same capacity.

Why does the NESC require minimum electrical clearances

The power conductors of overhead transmission lines are energized at high voltage and are insulated from people, vehicles, objects, buildings, and other conductors by air. The code requires minimum electrical distances (called clearances) to prevent flashovers. These minimum distances must be maintained under all environmental conditions (ice on the conductors, high winds) and all allowable power flow levels. Transmission Lines are designed to maintain minimum clearances under all conditions.

How are electrical clearances assured?

Prior to construction, engineering calculations estimate the sag of power conductors under heavy ice buildup (think of the "Canadian ice storm), the cyclic movement of power and shield wires under strong winds (ice galloping, subconductor oscillation) and the increase in sag due to thermal elongation at heavy power loads. The height and spacing of structures is selected to provide adequate electrical clearances. Once the line is built, maintenance and regular line patrols are implemented to limit vegetation growth under the line and to stop construction or piling of materials under the energized conductors.

Why are transmission conductors reinforced with steel?

Transmission line conductors consist of multiple aluminum strands. In climatic regions such as eastern Canada, where sag increases under occasionally severe ice buildup on conductors must be limited, a steel reinforcing core is used to limit the conductor sag. Steel is 3.5 times as stiff as aluminum and nearly 8 times as strong. Also, at high temperature, it limits sag increase with temperature and it is cheap. Steel reinforced aluminum conductors are used in about 80% of all the power lines in the world.

Can steel be replaced with other reinforcing materials?

Other materials can be used in place of steel. ACAR conductor replaces steel with a heat treated high strength aluminum alloy. ACCR from 3M uses core wires made of ceramic fibers in an aluminum matrix. ACCC from CTC (and a similar conductor from Showa electric in Japan) uses carbon fibers in a plastic resin matrix. In both these cases, the thermal elongation of the core is less than steel and the material cost is 3 to 10 times as much as steel. The composites are prone to shear failure and require more careful handling during construction.

Why does it take so long to develop new products for transmission lines?

Transmission lines last a long time and require little maintenance yet the components are subject to a very severe operating environment including high winds, periodic rain and ice on the conductors, rapid heating and cooling in response to changes in power flow and the line is expected to be functional almost all the time. Therefore, any product which is used in lines needs to be thoroughly tested prior to installation.

Could any new conductor solve all our transmission problems?

A new type of conductor could reduce electrical losses or allow increased current load in some lines but the limitations on power flow and reliability are much too complex to be solved by a new type of transmission line conductor. Voltage drop and electrical stability on long lines are not affected by the choice of conductor. Inadequate tree trimming and the need for routine inspections will not be overcome by a new type of conductor.

Does the use of a steel core in ACSR affect magnetic fields or ratings?

Magnetic fields are a function of the power conductor locations and the magnitude of current on the conductors. The steel core in power conductors has no effect on the magnetic fields that you experience standing under or near transmission lines. The presence of a steel core causes an increase in electrical losses of less than 5%.

How long do overhead lines last?

Transmission lines are designed for a 40 year life. In reality, many lines built in the 1920's and 1930's are still in use. While wood pole structures are not as durable as those made of steel, even wood poles can last for more than 40 years. Transmission line conductors from various environments have been tested, and even in corrosive environments, conductors can last 70 years or more.

Have there been problems with the introduction of new conductors in the past?

Yes. Quite a range of new conductors have been introduced in the last 40 years. Each has offered potential improvements and each has shown some difficulties relative to ACSR. The problems that developed over time were not obvious at the time that the new conductors were first evaluated, even after laboratory and field-experiments were completed. Examples include self-damping conductor (SDC), aluminum conductor steel supported (ACSS), T2, and aluminum conductor aluminum alloy reinforced (ACAR). The difficulties in installation and field repairs have resulted in little present use of SDC. Similarly, unforeseen problems with Aeolian vibration fatigue have led to a declining use of ACAR. ACSS and T2 have come to be widely used for lines requiring high operating temperatures and lines subject to ice galloping motions although in both cases these were significant installation problems and reliability issues that were not foreseen when introduced.