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IEEE Guide for Determining the Effects of High-Temperature Operation on Conductors, Connectors, and Accessories

IEEE Power Engineering Society

Sponsored by the
Transmission and Distribution Committee

IEEE

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Abstract: The purpose of this guide is to provide general recommendations for consideration when designing new overhead transmission lines that will be operated at high temperatures. It may also evaluate existing transmission lines for operation at higher temperatures. Although this guide is intended for overhead transmission lines, most of the discussion will also be applicable to distribution lines.
Keywords: conductors, conductor hardware, connectors, creep, high-temperature operation

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This introduction is not part of IEEE Std 1283-2004, IEEE Guide for Determining the Effects of High-Temperature Operation on Conductors, Connectors, and Accessories.

All annexes are only an informative part of this guide. The annexes are provided as either information or representative examples of some computational techniques in use today within the industry; however, they are not the only accepted techniques available nor are they to be considered the recommended techniques by the Task Force on The Effects of High Temperature Operation. Other techniques can be found in the references, bibliography, and other sources that provide equally acceptable results. The reader is encouraged to investigate any and all techniques to determine which best suit anticipated applications.

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IEEE Guide for Determining the Effects of High-Temperature Operation on Conductors, Connectors, and Accessories

1. Overview

The purpose of this guide is to provide general recommendations for consideration when designing new overhead transmission lines that will be operated at high temperatures. It may also evaluate existing transmission lines for operation at higher temperatures. Although this guide is intended for overhead transmission lines, most of the discussion will also be applicable to distribution lines.

The trend in most utilities today is to increase the capacity of their transmission lines wherever practical. It has become increasingly difficult to build new lines because of increased costs to obtain rights of way, public intervention, and state licensing requirements. These obstacles have significantly increased the cost and lead times required to place new lines into service. The lost revenue opportunities from power purchase/sale agreements with other systems because of limited transmission facilities can be substantial. Therefore, utilities are attempting to get as much capacity as is practical from the addition of new high-capacity lines or from the modification of existing lines for high-temperature operation.

In the past, utilities have typically been conservative in rating their lines due to the uncertainties in parameters that influence conductor temperature. Today, with a better understanding of actual ambient conditions and improvements in monitoring instruments and sophisticated analysis tools, utilities are rating lines at higher temperatures with the same or higher level of confidence than in the past. Many utilities have been increasing their transmission line's maximum conductor operating temperature as a way of increasing line capacity. Often higher operating temperatures are needed only for a few hours during the year. General concerns with increasing maximum operating temperature relate to accelerating the aging process of conductors, connectors, and conductor hardware plus maintaining adequate ground clearance for the safe operation of a line. Operating at a higher conductor temperature is acceptable if the associated negative effects are adequately understood, considered, and mitigated in the design or analysis of a line. Some effects of high-temperature operation to consider are as follows:

- Loss of strength in the conductors and connectors
- Increase in conductor sag resulting in reduced clearances
- Reduction of life and integrity of connectors
- Acceleration of component aging with higher operating temperatures
- Increase in resistive losses
- Potential damage to equipment attached to conductors (e.g., wave traps)

This guide is limited to discussing the effects of high-temperature operation on bare overhead transmission conductors, connectors, and conductor hardware. These effects are discussed to identify their impacts on safety, reliability, and economy. A few methods to mitigate some of these negative effects of high-temperature operation are also discussed.

2. References

This standard shall be used in conjunction with the following publications.

Accredited Standards Committee C2-2002, National Electrical Safety Code® (NESC®).[1]

Barrett, J. S., “High temperature operation of ACSR conductors,” *Proceedings of Seminar on Effects of Elevated Temperature Operation on Overhead Conductors and Accessories*, Atlanta, GA, pp. 25–36, May 1986

Bingham, A. H., Lambert, F. C., Monashkin, M. R., DeLuce, C. B., and Shaw, T. B., “An accelerated performance test of electrical connectors,” *IEEE Transactions on Power Delivery*, vol. PWRD-3, no. 2, pp. 762–768, Apr. 1988.

EEOI-NEMA Std CC 3-1973, Connectors for Use Between Aluminum or Aluminum-Copper Overhead Conductors.[2]

Harvey, J. R., “Creep of transmission line conductors,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-88, no. 4, pp. 281–285, Apr. 1969.

Harvey, J. R., “Effect of elevated temperature operation on the strength of aluminum conductors,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-91, no. 5, pp. 1769–1772, Sept./Oct. 1972.

Harvey, J. R., and Larson, R. E., “Creep equations of conductors for sag-tension calculations (abstract),” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-72, no. 2, p. 1729, July/Aug. 1972.

Harvey, J. R., and Larson, R. E., “Use of elevated temperature creep data in sag-tension calculations,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-89, no. 3, pp. 380–386, Mar. 1970.

Hickernell, F., Jones, A. A., and Snyder, C. J., “Hy-Therm copper—an improved overhead-line conductor,” *AIEE Transactions*, vol. 68, pp. 22–30, 1949.

Howitt, W. B., and Simpkins, T. E., “Effect of elevated temperature on the performance of conductor accessories (abstract),” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-72, no. 2, p. 1729, July/Aug. 1972.

Kidd, B. E., and Shaw, T. B., “Joint compounds and their relative effects in making good electrical connections,” *IEEE/PES T&D Conference*, Atlanta, GA, Apr. 1979.

“Limitations of the ruling span method for overhead line conductors at high operating temperatures,” *Report of IEEE WB on Thermal Aspects of Conductors, IEEE WPM 1998*, Tampa, FL, Feb. 3.

Morgan, V. T., *Effect of Elevated Temperature Operation on the Tensile Strength of Overhead Conductors*. IEEE Paper 95 WM 229-5 PWRD, 1995 IEEE/PES Winter Power Meeting.

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[1] The NESC is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

[2] NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (http://global.ihs.com/).

Nigol, O., and Barrett, J. S., “Characteristics of ACSR conductors as high temperatures and stresses,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-100, no. 2, pp 485–493, Feb. 1981.

3. Definitions, acronyms, and abbreviations

For the purposes of this standard, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B82] should be referenced for terms not defined in this clause.[3]

3.1 Definitions

3.1.1 annealing: A metallurgical process where high temperatures allow internal stress relaxation, which results in a softening and strength loss of the metal.

3.1.2 conductor: An overhead bare metal cable used to transmit electrical energy.

3.1.3 conductor hardware: Mechanical devices attached directly to the conductor that do not carry current.

3.1.4 connector: A current-carrying mechanical device used to join two or more conductors or a conductor to conductor hardware.

3.1.5 connector failure, electrical: Advanced connector aging where the locations for easily establishing current flow contact points are essentially exhausted.

3.1.6 connector failure, general: Thermal failure.

3.1.7 connector failure, mechanical: Advanced connector aging where the connector’s operating temperature is high enough to soften and eventually part the adjacent conductor.

3.1.8 connector failure, thermal: Advanced connector aging where the connector’s operating temperature is greater than the operating temperature of the conductor to which it is attached.

3.1.9 connector, full tension: A connector designed to join conductors and achieve at least 95% of the conductor’s rated tensile strength.

3.1.10 connector, limited tension: A connector designed to join conductors for low-tension applications.

3.1.11 creep, accelerated rate: An increase in a conductor’s creep rate over general creep rate, usually associated with elevated temperature operation.

3.1.12 creep, general: The accumulative nonelastic elongation of a conductor under tension over an extended period of time at modest temperatures usually not in excess of approximately 75 °C.

3.1.13 creep, high temperature: The creep a conductor experiences over a period of time operating at conductor temperatures in excess of approximately 75 °C.

3.1.14 high-temperature operation: Operating conductors and connectors at temperatures where thermal effects can impact the safety, reliability, and life of the transmission line.

3.1.15 loss of strength: The partial loss of a conductor’s mechanical strength through annealing.

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[3] The numbers in brackets correspond to those of the bibliography in Annex A.

3.1.16 maximum conductor operating temperature: The maximum conductor temperature at which the transmission line can operate with acceptable performance in safety and reliability. The line's maximum temperature is usually dictated by either ground clearance or loss of conductor strength.

3.1.17 ruling span: A representative level span for a line section of contiguous unequal suspension spans that approximates changing conductor temperature, creep, and weather conditions.

3.1.18 steel core: The inner strength member of a composite conductor composed of steel strand(s).

3.1.19 steel strands, aluminized: Steel core wire strands coated with aluminum to reduce corrosion of the steel strands.

3.1.20 steel strands, aluminum clad: Steel core wire strands clad with aluminum to reduce corrosion and increase conductance.

3.1.21 steel strands, galvanized: Steel core wire strands coated with zinc to reduce corrosion of the steel strands.

3.2 Acroynms and abbreviations

AAAC	all-aluminum alloy conductor
AAC	all-aluminum conductor
AACSR	aluminum alloy conductor steel reinforced
ACAR	aluminum conductor alloy reinforced
ACSR	aluminum conductor steel reinforced
ACSS	aluminum conductor steel supported
Cu	copper

4. Conductors

4.1 Conductor types

Many different types of bare overhead conductors transmit electrical energy. The most common bare overhead conductors are constructed from either copper, aluminum, or their alloys and can be further strength reinforced with steel. Most typical types are AAC, AAAC, ACAR, ACSR, AACSR, ACSS, and Cu.

4.2 Stranding types

The two conductor stranding types typically used to construct bare overhead conductors are round- and trapezoidal-shaped strands.

4.3 High-temperature creep

4.3.1 Introduction to creep

A conductor under tension undergoes nonelastic elongation over a period of time (usually measured in years). This elongation is called creep. The magnitude and rate of creep are a function of the conductor's composition, stranding, line tension, and operating temperature.

4.3.2 Accelerated creep caused by high-temperature operation

Generally stated, high-temperature creep should be considered when conductor temperatures exceed 75 °C. Because aluminum has a much higher creep rate than steel, all-aluminum type conductors such as AAC, AAAC, and ACAR are much more susceptible to creep as well as high-temperature creep. Conversely, copper- and steel-supported aluminum conductors (Cu, ACSR, and AACSR) are less affected by high-temperature creep. Prestressed ACSS has its aluminum strands fully annealed and consequently carries negligible mechanical load; hence, all load is carried by the steel core, which is generally not affected by creep below 200 °C.

4.3.3 Effect on sag-tension

At elevated temperatures, conductor sags and tensions are affected by both an accelerated creep rate and the thermal expansion of conductor strand materials. Aluminum strands expand at twice the rate of steel strands. As a result of different expansion rates, as well as increased creep at elevated temperatures, the effect of high-temperature operation on the sag of all-aluminum conductors is greater than the effect for composite conductors. In a composite conductor, as temperature increases, the conductor tension transfers from the aluminum strands to the steel strands. This load transfer decreases the creep rate on the aluminum and reduces the elongation of the conductor because of thermal expansion. If the tensile load is completely transferred, or “off-loaded” to the steel, only the creep and thermal expansion of the steel strands further affect conductor sag.

The elevated temperature effect on sags and tensions for high steel composition conductors is reduced because the aluminum may off-load at relatively low temperatures (greater than 7.5% steel by area). As the steel has picked up most of the conductor’s mechanical load at relatively low operating temperatures, the aluminum’s influence on sags and tensions is minimal. Hence, high steel reinforced conductors are less susceptible to high-temperature creep than are conductors with lower steel ratios.

For modest operating temperatures, ACSS conductors quickly off-load the aluminum strands (especially if prestressed). Hence, high-temperature effects on sags and tensions for ACSS conductors are smaller than are high steel conductors and exhibit negligible high-temperature creep below 200 °C.

4.3.4 Creep predictor equations

See Annex A for a technique to predict conductor creep, and Annex B for a computational example of the technique to quantify high-temperature creep and its effect on conductor sag [see IEEE Paper C72 190-2 and Harvey (1969)].[4]

4.4 Loss of strength and annealing

4.4.1 Introduction to conductor strength

Conductors are made of materials designed to operate best at or near ambient temperature. Operating conductors at elevated temperatures, above approximately 75 °C for copper and 93 °C for aluminum, raise many questions and issues, including the loss of conductor strength because of annealing.

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[4] Information on references can be found in Clause 2.

4.4.2 Physics of conductor strength

Conductors derive their strength from the metallurgical properties of the parent metal and from cold working the strands during the rolling and/or drawing process used to shape the strands. This cold working enhances the strand’s tensile strength by stretching and locking up atomic grain boundaries and atomic lattices. For example, the process of cold working pure aluminum (1350 alloy) produces about 70% of the strand’s overall strength.

4.4.3 High-temperature effects on conductor strength

Loss in conductor strength is the result of annealing in the aluminum or copper strands by relaxing the mechanical stress in the grain boundaries and lattices achieved during cold working. The extent of this loss is a function of the material’s composition, its operating temperature, the accumulated length of time at this operating temperature, and may also depend on conductor tension for copper. The aluminum begins to lose strength when operated above 93 °C. Copper loses strength with high-temperature operation beginning at about 75 °C. Note that the loss of strength of copper can be variable from one type of copper material to another. For effects of temperature and tension on the annealing of copper, see Hickernell et al. (1949). The strength of a conductor’s steel core is not affected by temperatures below 200 °C.

4.4.4 Annealing effects on modulus of elasticity

As noted, aluminum and copper strands lose strength by annealing, which usually does not have a large effect on the final modulus of elasticity of all-aluminum or copper conductors. However, for highly annealed composite conductors, this loss in strength under heavy mechanical loads (i.e., ice) can permanently shift a large percentage of the tensile load from the aluminum strands onto the steel core. This redistribution of load causes extra conductor elongation, hence, greater sags than originally designed.

4.4.5 Predictor equations

Predictor equations for conductor loss of strength tend to simplify a complex phenomenon. Most predictor equations acknowledge the time and temperature dependence of strength loss, but they are still an empirical aggregate of several processes occurring simultaneously. Such equations should be limited to assisting the engineer in understanding some of the impacts of high-temperature operation on conductors and providing general quantitative predictions of strength loss. Annex C contains one method for calculating the remaining strength of a conductor as a percentage of its initial strength [see Harvey (1972)]. Other techniques are also available and should be investigated to determine which approach best suits anticipated applications [see Morgan (1995)].

4.5 High-temperature effects on conductor core

4.5.1 Introduction to steel core

Composite conductors (i.e., ACSR, AACSR, etc.) are stranded aluminum conductors reinforced with strands of steel wires to increase conductor strength.

The core wires of ACSR may be zinc-coated steel (galvanized) available in various strand weight thicknesses (Class A, B, or C), zinc-5% aluminum-mischmetal alloy-coated steel core wire, aluminum coated steel (aluminized), or aluminum-clad steel strands. Galvanized or aluminized coatings are applied to reduce corrosion of the steel wires. Aluminum clad strands have a greater aluminum thickness for increased conductance and greater corrosion protection than aluminized strands. They also provide an aluminum-to-aluminum contact between the core and outer aluminum wires to prevent the possibility of galvanic corrosion.

4.5.2 High-temperature effects on galvanized steel core

Laboratory investigations have shown that high-temperature operation of conductors with a galvanized steel core can be limited by the adherence of zinc coating to steel core wires. Some important generalizations and observations about high-temperature operation of galvanized steel core wire are as follows:

- The steel strands of ACSR conductors will run hotter than the aluminum strands. Tests show temperature gradients between the steel core and outer aluminum strands can be as high as 10% of the conductor surface temperature for new conductors and 20% for old conductors, depending on stranding, age, and ambient conditions.
- The zinc coating does not adhere well to the core wires at temperatures in excess of 200 °C. Operating temperatures above this value will decrease the life expectancy of in-service conductors because of reduced corrosion resistance from subsequent pitting of the steel strands.
- Temperatures in excess of 300 °C cause the zinc surface layer to alloy with the underlying steel. This alloying forms brittle compounds that have a tendency to flake and spall; plus they also tend to lower the corrosion resistance of the galvanized wire. Additionally, brittle cracks in the zinc alloy layer will greatly increase the underlying steel’s susceptibility to fatigue. Such temperatures cause a reduction in steel hardness and tensile strength.

4.5.3 High-temperature effects on aluminum-clad core

The mechanical characteristics of an aluminum-clad core are similar to those of a steel core because of their comparable steel-strength-to-total-core-strength ratios (approximately 0.94). High-temperature effects on aluminum-clad strands are minimal up to approximately 325 °C. Above such temperatures, the tensile strength of these strands exhibit a smooth degradation with temperature.

4.6 High-temperature effects on sags and tensions

4.6.1 Introduction to conductor sag-tension models

A conductor will elongate both elastically and nonelastically because of changes in temperature and tension. At a constant temperature and within the elastic limit of a material, a uniform material will increase in length at a linear rate with increases in tension. Composite conductors made of materials having different modulus of elasticities, such as steel-reinforced conductors, will exhibit more complex sag-tension characteristics. As tension increases on composite conductors, the tension supported by each material will increase at a varying rate. The overall effect of this process is a nonuniform distribution of mechanical load between the two materials with changing tension. In steel-reinforced conductors, the percentage of load supported by the steel core increases as conductor temperature increases.

4.6.2 High-temperature effects on sags and tensions

As discussed in 4.3, high-temperature operation of conductors can increase the amount of creep they experience. As conductor materials creep, conductor tensions decrease and sags increase. Some types of conductors are more affected by high-temperature operation than are others. Steel-reinforced conductors (ACSR, AACSR, ACSS) and copper conductors (Cu) are affected less by elevated temperature creep than are all-aluminum conductors (AAC, AAAC, ACAR). The increase in sag can result in electrical clearance problems to ground or other objects below the conductors. It is, therefore, important to predict the effect of high-temperature operation on conductor sag.

One technique for predicting this change in sag and tension using a sag-tension program is shown in Annex A and illustrated in Annex B. This prediction technique models elevated temperature creep as an equivalent increase in conductor temperature to achieve the same net increase in conductor length. This calculated temperature increase is then added to standard design temperatures used for sag-tension calculations. When these new temperature values are used for calculating sags and tensions, they predict the added sag resulting from high-temperature operation and elevated temperature creep.

For composite conductors, most sag-tension programs assume the mechanical load carried by aluminum strands completely off-loads to the core above a particular conductor temperature. Some studies have indicated this off-loading may occur only partially or not at all [see Barrett (1986) and Nigol and Barrett (1981)]. The same studies attribute this phenomenon to a significant conductor thermal gradient forcing the inner constricted aluminum layers into compression and hence adding to the core's tensile loading. Thus, high-temperature sags of multiple layer ACSR conductors may be larger than those predicted by most sag-tension programs. If conductors are operated above the "off load temperature," sufficient clearance margins should be employed to account for the uncertainty in the effects of aluminum compressive loads on conductor sags. Further research and field investigations into sag and tension effects for ACSR conductors, particularly at high operating temperatures, would be beneficial to the industry to better understand and quantify their impacts on conductor clearances.

4.6.3 Considerations for high-temperature effects on ruling span method

The ruling span method converts a contiguous series of unequal suspension spans into a single level span that predicts changes in conductor tension with changing conductor temperature. This predictor is viable as long as conductor temperature does not depart excessively from sagging temperature. The ruling span method assumes infinite insulator string length, with tension equalization being achieved through string movement between varying span lengths. The method assumes the effects of finite insulator string length and the resulting restraining loads carried by the supporting towers to be negligible.

Operating conductor temperatures exceeding about 100 °C combined with the short suspension strings of lower voltage lines can compromise the ruling span method and result in significant sag changes greater than predicted by ruling span calculations. These excessive sags will generally appear in spans shorter than the ruling span, but not necessarily in the shortest span nor short spans adjacent to long spans [see Report of IEEE WB on Thermal Aspects of Conductors (1998)].

Furthermore, the behavior of sags and tensions during high conductor temperatures in an irregular line section is complex (i.e., spans with large differences in conductor attachment elevations). Caution should be exercised when increasing conductor operating temperature for such line sections when ground clearance approaches design or safety code limits.

4.6.4 Consideration for high-temperature operations and clearances

The effects of high-temperature conductor operation on electrical clearances must be considered whenever it is anticipated that conductor temperatures will exceed the line's original maximum design temperature. Additionally, elevated temperature creep should also be included when conductor temperatures exceed about 75 C for all-aluminum conductors and low steel ACSR conductors (less than 7.5% steel by area), and 100 C for all other steel-reinforced conductors. In general, if elevated temperature creep is less than general creep, then elevated temperature creep has no significant effect on final sags and clearances. However, if elevated temperature creep exceeds general creep, then its effects on sags and clearances should be considered (see 4.3). Clearances should be in compliance with applicable safety codes and local requirements, such as the National Electrical Safety Code (Accredited Standards Committee C2-2002).

5. Connectors

Connectors, as used in this guide, refer to current-carrying devices that mechanically join two or more conductors for the purpose of providing a continuous electrical path. Connectors are generally used to splice, deadend, terminate, and tap conductors. In addition to electrical requirements, transmission connectors are also required to support high mechanical loads typically found in transmission spans between adjacent towers or poles.

5.1 Design of connectors

A quality connector design will provide suitable conductance through the connector, low resistance of the contact interfaces, adequate strength for intended mechanical loads, and an appropriate amount of heat radiating surface area.

5.1.1 Limited tension connectors

Limited tension connectors are primarily designed to join conductors that are under little or no mechanical tension. They are typically used to splice the ends of two conductors together in a low tension application, tap a second conductor from a continuous run conductor, or terminate the end of a conductor in a low tension application. Typical types of limited tension connectors are bolted connectors, compression connectors, formed-wire connectors, wedge type connectors, and implosive connectors. Because of their limited mechanical holding strength, that portion of the connector in contact with the conductor is generally less in area than that of its full tension counterpart.

5.1.2 Full tension connectors

In addition to providing continuity in the electrical path, full tension connectors are also designed to provide adequate mechanical strength to fully develop the conductor’s strength. Splice connectors are used to join the ends of the conductors in-span, and deadends are used to join conductors to attachment hardware on deadend structures. Typical types of full tension connectors are one- and two-piece compression connectors, formed-wire splices, implosive connectors, and wedge type connectors. Although the term “full tension” is commonly used for the mechanical holding strength of splices and deadends, they are typically designed to hold a minimum of 95% of the conductor’s rated strength.

5.2 Connector high-temperature operation

The main consideration for connectors when evaluating elevated conductor temperature operation is its impact on the connector’s long-term service. High-temperature excursions of connectors increase their electrical, mechanical, and thermal stresses, which, if severe and/or frequent, can undermine the integrity of the connector. Failure of connectors can be precipitated by high current and/or high-temperature operation. Such failures can be difficult to predict and find. In addition, they are usually expensive, resulting in extensive field work to repair and a loss in transmission capacity. As the final stage of failure is parting of the conductor, there are also safety issues to consider.

5.2.1 Connector breakdown process

A connector accomplishes current transfer through numerous contact points between the connector and the conductor. High current densities and high operating temperatures tend to encourage the buildup of resistive compounds at these contact point sites, which reduce their effective size or completely close off current flow. The connector will reestablish new contact points at locations within the connector that do not have a buildup of resistive compounds. The reestablishment of contact points within the connector can be thought of as an “aging” process, where the connector will continue to provide good performance as long as there are locations where contact points can be easily established.

Once the connector has aged such that all locations for easily establishing contact points are exhausted, the connector is forced to establish contact points through resistive compounds to reach the parent metal, which increases the overall resistance of the connector, its operating temperature, and current density within the remaining contact points. Once in this mode of operation, higher current densities and operating temperatures encourage further buildup of resistive compounds that further drive up current density and operating temperature resulting in electrical failure. This electrical failure of a connector will mature into a thermal failure that can be detected using thermal sensing equipment. If allowed to continue, the thermal failure will induce mechanical failure where the connector locally heats the conductor to temperatures where it becomes so hot, the conductor softens and eventually parts.

5.2.2 High-temperature effects on connectors

Elevated temperature operation of conductors increases the current density and operating temperature of associated connectors. This increase in service duty for connectors will accelerate their aging process, effectively reducing service life. The amount of accelerated aging a connector experiences is directly related to the magnitude and frequency of elevated current and operating temperature excursions. Unfortunately, the relationship between connector aging and service duty is nonlinear, and little success has been achieved in directly quantifying that relationship.

Most well-designed connectors, when properly installed, can operate at high current densities and high conductor temperatures with acceptable long-term service. These connector designs have traditionally been evaluated using the industry standard current cycle test (see EEOI-NEMA Std CC 3-1973). Current cycling the connector results in thermal expansion and contraction of the electrical contact interface, which tends to break down the contact points. Although this standard test identifies procedures and qualification criteria for connector use under normal operating conditions, it does have its limitations. The test requires a modest conductor temperature of only 100 °C above ambient temperature and does not evaluate the effects of fault current nor atmospheric or industrial contamination. Recognizing that generalizations should be used cautiously, connectors that maintain satisfactory contact pressure over adequate contact areas, plus maintain low operating temperatures, will exhibit better long-term service than connectors exhibiting lesser values of contact pressure and/or higher operating temperature.

5.2.3 Connector failure

For this guide, connectors shall be considered failed if their operating temperature exceeds the temperature of the conductor to which they are attached. It can be argued that a connector operating in this mode has previously failed, and it can also be argued a connector has not failed until the conductor has parted interrupting electrical continuity. However, “failed” field connectors are difficult to detect until operating in thermal failure mode, and such operation is usually a precursor to imminent conductor parting.

5.2.4 High-temperature effects on connector joint compound

Most aluminum connectors (particularly compression type) employ a viscous compound in the interface between the connector and underlying conductor. The primary purpose of the joint compound is to provide a barrier preventing moisture and other contaminants from leaching into the joint. Numerous excursions to high operating temperatures [connector temperatures above 93 °C; see Kidd and Shaw (1979)] can degrade the joint interface through compound evaporation in place and/or boiling the compound out of the connector–conductor joint. Joint compound evaporation will leave a shrunken and hardened residue no longer effective as a moisture barrier, and joint compound boiling expels the compound rendering a fitting no longer protected against moisture and contaminants leaching into the connector–conductor interface. The presence of moisture and contaminants in the joint will accelerate the connector’s aging process and effectively shorten the connector’s service life.

5.3 Analysis of connector high-temperature operation

5.3.1 Selecting new connectors

When designing overhead power lines for high-temperature operation, consideration should be given to the conductor temperatures at which the connectors were tested. Prudence dictates that connectors designed for high-temperature operation should be tested and qualified for temperatures in excess of those expected in service. It is well known that electrical connectors that operate satisfactorily at one conductor temperature may not be suitable for higher conductor temperatures.

5.3.2 Evaluating existing connectors

When evaluating existing connectors for operation at higher temperatures, a review of the standards against which the connectors were designed and tested will help in evaluating whether they are acceptable for increased service duty. Operating electrical connectors at temperatures above those for which they were designed can be risky. If a standard current-cycle test is not available, performing the same on a specific connector design would provide additional information in evaluating the limits of a connector's service duty.

5.4 Mitigation of connector high-temperature operation

5.4.1 Reinforcing existing connectors

Existing connectors that are suspected of being inadequate for high-temperature operation can be shunted to reduce their electrical loading and prolong their service life. Shunts provide an alternative path for current flow, thereby reducing the connector's current density and operating temperature. The reduction in connector current density retards the connectors aging process, which enhances its long-term service life. Shunting of marginal connectors to enhance long-term survival is appropriate for field connectors that have not yet failed.

5.4.2 Repair of failed connectors

Repair of failed connectors where the conductor has parted involves cutting out the connector and adjacent annealed conductor, thoroughly cleaning the undamaged conductor ends, and installing new connectors. When connectors are found failed but have not parted the conductor (usually with some type of thermal-vision device), the repair is the same as a parted conductor; cut out the failed connector, and properly install a new replacement. As an interim measure, however, the failed connector can be shunted, which reduces current density and operating temperature, thereby retarding the breakdown process.

6. Conductor hardware

Conductor hardware, as used in this guide, refers to non-current-carrying devices attached directly to the conductor. Conductor hardware includes such standard devices as suspension clamps (with and without armor rod), bolted strain clamps, armor grip suspension, dampers, spacers, and spacer-dampers. Insulators and other hardware not directly attached to the conductor are beyond the scope of this guide. Connectors are covered in Clause 5.

6.1 Metallic conductor hardware

Metallic conductor hardware for aluminum conductors is fabricated primarily from aluminum alloys. Hardware for copper conductors is fabricated primarily from copper alloys. This practice recognizes the galvanic reaction between copper and aluminum when the two dissimilar metals are brought together in the presence of moisture. Galvanized ferrous hardware components have had extensive use because of their high strength-to-weight ratio and their being relatively galvanicly inert to both aluminum and copper in mild atmospheres.

6.1.1 High-temperature effects of ferrous conductor hardware

Ferrous hardware, which surrounds, or partly surrounds, a conductor, is subject to hystereses and eddy current losses because of the magnetic flux associated with conductor current flow. These losses manifest as heat gain within the hardware and, hence, increase operating temperature. Hardware operating temperatures greater than the conductor’s allowable temperature for annealing may result in an unacceptable localized loss of conductor strength. The localized loss of conductor strength is confined to the conductor directly under and adjacent to the hardware.

Heat gain caused by hystereses and eddy current losses in ferrous hardware is a function of conductor current magnitude and hardware thermal conductivity. Convection and radiation heat losses from the ferrous hardware are primarily a function of hardware surface area and surrounding ambient conditions. Hence, ferrous hardware operating temperatures will fluctuate in response to changing current flow and ambient conditions such that an equilibrium hardware temperature will be maintained balancing heat gain against heat loss. This equilibrium temperature will be largely influenced by current magnitude, ambient temperature, and a hardware’s mass-to-surface-area ratio.

Conductor hardware is employed in numerous applications to support and protect the conductor and is available in many different sizes and shapes. Smaller versions of ferrous hardware have relatively low mass in comparison with their surface area and usually operate at temperatures well below the conductor’s allowable annealing temperature regardless of current. Conversely, larger versions of ferrous hardware have a mass-to-surface-area ratio that can result in hardware temperatures greater than the conductor’s allowable annealing temperature at higher currents. Hardware large enough to produce localized conductor temperatures of concern are usually confined to suspension and strain clamps, but they can be any ferrous device surrounding the conductor with a large mass-to-surface-area ratio. Published literature quantifying localized conductor temperature increases caused by ferrous hardware as a function of current flow is limited.

Mitigating the effects of localized heating under ferrous hardware usually involves either limiting the current rating of a line, limiting the cumulative time a conductor can operate at an elevated rating, or replacing the hardware with nonferrous hardware. As the possible conductor/hardware combinations are extensive, no preferred mitigating technique has emerged within the utility industry. Such mitigation tends to be utility specific and often involves a combination of various techniques.

6.1.2 High-temperature effects with nonferrous conductor hardware

Nonferrous conductor hardware does not have internal heat generation because of conductor current flow. Such hardware also increases the local radiating surface area. Hence, nonferrous hardware usually operates cooler than does the conductor to which it is attached.

6.2 Nonmetallic conductor hardware

Nonmetallic conductor hardware is generally limited to elastomeric compounds that serve as compressive "bushings" within a hardware assembly. Compression bushings are typically used in spacers, spacer-dampers, and armor grip suspension clamps to provide a resilient interface between the conductor and the hardware.

Little work has been published concerning the effects of high-temperature operation on elastomeric hardware components. During and after high-temperature excursions, the elastomeric components must retain their resilient and semiconductive properties for long-term survival. Loss of such properties can result in component deterioration and/or component failure.

Annex A

(informative)

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Annex B

(informative)

Creep predictor equations for high-temperature operation

B.1 Definition of terms

ε_c	primary creep strain (units/unit)
ε	strain—increase in length/original (units/unit)
$\Sigma\varepsilon_T$	increase in conductor strain because of elevated temperature operation (units/unit)
σ	stress—tension/area (N/mm^2, lbf/in^2)
α	coefficient of thermal expansion ([units/unit]/ºC)
T	elapsed time (hours)
T	conductor temperature (ºC)
ΔT	temperature change value (ºC)
A_{EC}	area of aluminum strands (mm^2, in^2)
A_{ST}	area of steel strands (mm^2, in^2)
A_T	total conductor area (mm^2, in^2)
%RS	tension as a percentage of the rated strength (%)

B.2 Formula constants (metric)

Table B.1—Creep predictor formula constants (metric)

	7 strands	**19 strands**	**37 strands**	**61 strands**
K_1	1.3600	1.2900	1.2300	1.1600
K_2	0.8400	0.7700	0.7700	0.7100
M_1	0.0148	0.0142	0.0136	0.0129
M_2	0.0090	0.0090	0.0084	0.0077
G	0.7100	0.6500	0.7700	0.6100

B.3 Formula constants (English)

Table B.2—Creep predictor formula constants (English)

	7 strands	19 strands	37 strands	61 strands
K_3	0.002100	0.002000	0.001900	0.001800
K_4	0.001300	0.001200	0.001200	0.001100
M_3	0.000023	0.000022	0.000021	0.000020
M_4	0.000014	0.000014	0.000013	0.000012
G	0.001100	0.001000	0.001200	0.000940

NOTE—K_1, K_3, M_1, and M_3 are for wire bar rolled rod, and K_2, K_4, M_2, and M_4 are for continuous cast (rolled) rod.[7]

B.4 Predictor equations

B.4.1 All-aluminum conductors

Room temperature: (metric)

AAC: $\varepsilon_c = K \sigma^{1.3} t^{0.16}$

AAAC: $\varepsilon_c = G \sigma^{1.3} t^{0.16}$

ACAR: $\varepsilon_c = (0.19 + 1.36 A_{EC}/ A_T) (T^{1.4} \sigma^{1.3} t^{0.16})$

Room temperature: (English)

AAC: $\varepsilon_c = K \sigma^{1.3} t^{0.16}$

AAAC: $\varepsilon_c = G \sigma^{1.3} t^{0.16}$

ACAR: $\varepsilon_c = (0.0003 + 0.0021 A_{EC}/ A_T) (T^{1.4} \sigma^{1.3} t^{0.16})$

Elevated temperature: (metric)

AAC: $\varepsilon_c = M T^{1.4} \sigma^{1.3} t^{0.16}$

AAAC: $\varepsilon_c = 0.0077 T^{1.4} \sigma^{1.3} t^{0.16}$

ACAR: $\varepsilon_c = (0.0019 + 0.012 A_{EC}/ A_T) (T^{1.4} \sigma^{1.3} t^{0.16})$

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[7] Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the guide.

Elevated temperature: (English)

AAC: $\varepsilon_c = M\, T^{1.4}\, \sigma^{1.3}\, t^{0.16}$

AAAC: $\varepsilon_c = 0.000012\, T^{1.4}\, \sigma^{1.3}\, t^{0.16}$

ACAR: $\varepsilon_c = (0.000003 + 0.000019\, A_{EC}/ A_T)\, (T^{1.4}\, \sigma^{1.3}\, t^{0.16})$

B.4.2 Steel-reinforced conductors (ACSR and AACSR)

Room temperature:

Aluminum strands drawn from hot-rolled rod:

$$\varepsilon_c = 2.4\, (\%RS)^{1.3}\, t^{0.16}$$

Aluminum strands drawn from continuous cast rod:

$$\varepsilon_c = 1.1\, (\%RS)^{1.3}\, t^{0.16}$$

Elevated temperature:

Only for conductors with less than 7.5% steel by area:

$$\varepsilon_c = .24\, (\%RS)^{1.3}\, T\, t^{0.16}$$

Elevated creep strain for conductors with a steel core equal to or greater than 7.5% steel by area can be ignored.

B.4.3 Temperature change value

The temperature change value is a calculated temperature that approximates the net increase in microstrain because of elevated temperature creep over general creep.

$$\Sigma\varepsilon_T = \alpha\, \Delta T \quad \text{or} \quad \Delta T = \Sigma\varepsilon_T/\alpha$$

where

$$\Sigma\varepsilon_T = \varepsilon_{@high} - \varepsilon_{@ambient}$$

$\varepsilon_{@ambient}$ is the strain caused by room temperature creep only, and $\varepsilon_{@high}$ is the strain caused by elevated (high) temperature creep.

Typical values for the coefficient of thermal expansion (α) are as in Table B.3.

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Table B.3—Conductor coefficient of thermal expansion values

Conductor type	α
Aluminum	23.0×10^{-6}
ACSR (18/1)	21.1×10^{-6}
ACSR (26/7)	18.9×10^{-6}
ACSR (36/1)	22.0×10^{-6}
ACSR (45/7)	20.7×10^{-6}
ACSR (72/7)	21.6×10^{-6}
ACSR (76/19)	21.1×10^{-6}
ACSR (84/19)	19.4×10^{-6}

B.5 Use of predictor equations

a) Use standard graphic or computer sag and tension methods to predict the sags and tensions without elevated creep for the given situation.
b) Compute the creep at ambient temperature.
c) Compute the creep at the first elevated temperature.
d) Compute how many hours it would take to get this same amount of creep at the second elevated temperature.
e) Repeat item a) and item b) for all elevated temperatures.
f) Calculate the temperature change value.
g) Calculate the final sag after elevated temperature creep by adding this temperature change value to the temperatures used in the standard sag and tension calculation.

The creep predictor equations presented here were developed by Harvey and Larson (1970).

Annex C

(informative)

Example of calculating elevated temperature creep and its effect on conductor sag

C.1 Situation

Assume a 402.8 mm^2 (795 kcmil), 37 strand, AAC, continuous cast, “Arbutus” conductor, which has a 243.8 m (800 ft) ruling span and a maximum light loading tension of 25.1 kN (5644 pounds-force). The designer predicts that it will operate for 1000 hours at 100 ºC, 100 hours at 125 ºC, and 10 hours at 150 ºC. How much additional sag will occur because of this elevated temperature operation?

C.2 Calculation

Standard graphic or computer sag and tension methods predict the sags and tensions for the given situation in Table C.1.

Table C.1—Example sag and tension values

Temperature		Sag		Tension	
ºC	**ºF**	**m**	**ft**	**kN**	**lbf**
16	60	5.85	19.2	13.90	3125
100	212	8.56	28.1	9.51	2138
125	257	9.27	30.4	8.81	1981
150	302	9.91	32.5	8.25	1854

To compute the creep at ambient temperature (16 ºC) for 10 years: (metric)

$$\begin{aligned}\varepsilon_c &= K\,\sigma^{1.3}\,t^{0.16}\\ &= 0.77\,(13\,900/402.8)^{1.3}\,(24\text{ hr}\times 365\text{ days}\times 10\text{ yrs})^{0.16}\\ &= 474.9\ \mu\varepsilon\end{aligned}$$

To compute the elevated temperature creep for 1000 hours at 100 ºC: (metric)

$$\begin{aligned}\varepsilon_c &= M\,T^{1.4}\,\sigma^{1.3}\,t^{0.16}\\ &= 0.0084\times(100)^{1.4}\,(9510/402.8)^{1.3}\,(1000)^{0.16}\\ &= 975.7\ \mu\varepsilon\end{aligned}$$

To compute how many hours it would take to get this same amount of creep (975.7) at 125 ºC: (metric)

$$\varepsilon_c = M\, T^{1.4}\, \sigma^{1.3}\, t^{0.16}$$

$$975.7 = 0.0084\, (125)^{1.4}\, (8810/402.8)^{1.3}\, t^{0.16}$$

$$t = 264 \text{ hours}$$

To compute the elevated temperature creep for 100 hours at 125 ºC: (metric)

$$\varepsilon_c = M\, T^{1.4}\, \sigma^{1.3}\, t^{0.16}$$

$$= 0.0084\, (125)^{1.4}\, (8810/402.8)^{1.3}\, (100 + 264)^{0.16}$$

$$= 1027.0\ \mu\varepsilon$$

To compute how many hours it would take to get this same amount of creep (1027.0) at 150 ºC: (metric)

$$\varepsilon_c = M\, T^{1.4}\, \sigma^{1.3}\, t^{0.16}$$

$$1027.0 = 0.0084\, (150)^{1.4}\, (8250/402.8)^{1.3}\, t^{0.16}$$

$$t = 126 \text{ hours}$$

To compute the elevated temperature creep for 10 hours at 150 ºC: (metric)

$$\varepsilon_c = M\, T^{1.4}\, \sigma^{1.3}\, t^{0.16}$$

$$= 0.0084\, (150)^{1.4}\, (8250/402.8)^{1.3}\, (10 + 126)^{0.16}$$

$$= 1039.8\ \mu\varepsilon$$

To compute the temperature change value that approximates the net increase in microstrain caused by elevated (high) temperature creep over general creep:

$$\Delta T = (\varepsilon_{c@high} - \varepsilon_{c@ambient})/\alpha$$

$$= (1039.8 \times 10^{-6} - 474.9 \times 10^{-6})/(23 \times 10^{-6})$$

$$= 24.6\ ºC\ [76.3\ ºF]$$

Calculate the final sag after elevated temperature creep by adding the 24.6 ºC [76.3 ºF] temperature change value to the temperatures used in the standard sag and tension calculation (i.e., to get the elevated temperature final sag at 100 ºC, calculate the final sag at 124.6 ºC).

To compute the creep at ambient temperature (60 ºF) for 10 years: (English)

NOTE—795 kcmil is 0.6245 in^2.

$$\varepsilon_c = K\, \sigma^{1.3}\, t^{0.16}$$

$$= 0.0012\, (3125/0.6245)^{1.3}\, (24 \text{ hr} \times 365 \text{ days} \times 10 \text{ yrs})^{0.16}$$

$$= 477.6\ \mu\varepsilon$$

To compute the elevated temperature creep for 1000 hours at 100 ºC: (English)

$$\begin{aligned}\varepsilon_c &= M\,T^{1.4}\,\sigma^{1.3}\,t^{0.16}\\ &= 0.000013\times(100)^{1.4}\,(2138/0.6245)^{1.3}\,(1000)^{0.16}\\ &= 974.5\ \mu\varepsilon\end{aligned}$$

To compute how many hours it would take to get this same amount of creep (974.5) at 125 ºC: (English)

$$\begin{aligned}\varepsilon_c &= M\,T^{1.4}\,\sigma^{1.3}\,t^{0.16}\\ 974.5 &= 0.000013\,(125)^{1.4}\,(1981/0.6245)^{1.3}\,t^{0.16}\\ t &= 264\ \text{hours}\end{aligned}$$

To compute the elevated temperature creep for 100 hours at 125 ºC: (English)

$$\begin{aligned}\varepsilon_c &= M\,T^{1.4}\,\sigma^{1.3}\,t^{0.16}\\ &= 0.000013\,(125)^{1.4}\,(1981/0.6245)^{1.3}\,(100+264)^{0.16}\\ &= 1025.9\ \mu\varepsilon\end{aligned}$$

To compute how many hours it would take to get this same amount of creep (1025.9) at 150 ºC: (English)

$$\begin{aligned}\varepsilon_c &= M\,T^{1.4}\,\sigma^{1.3}\,t^{0.16}\\ 1025.9 &= 0.000013\,(150)^{1.4}\,(1854/0.6245)^{1.3}\,t^{0.16}\\ t &= 126\ \text{hours}\end{aligned}$$

To compute the elevated temperature creep for 10 hours at 150 ºC: (English)

$$\begin{aligned}\varepsilon_c &= M\,T^{1.4}\,\sigma^{1.3}\,t^{0.16}\\ &= 0.000013\,(150)^{1.4}\,(1854/0.6245)^{1.3}\,(10+126)^{0.16}\\ &= 1038.0\ \mu\varepsilon\end{aligned}$$

To compute the temperature change value that approximates the net increase in microstrain due to elevated (high) temperature creep over general creep:

$$\begin{aligned}\Delta T &= (\varepsilon_{c@high} - \varepsilon_{c@ambient})/\alpha\\ &= (1038.0\times10^{-6} - 477.6\times10^{-6})/(23\times10^{-6})\\ &= 24.4\ ºC\ [75.9\ ºF]\end{aligned}$$

Calculate the final sag after elevated temperature creep by adding the 24.4 ºC [75.9 ºF] temperature change value to the temperatures used in the standard sag and tension calculation (i.e., to get the elevated temperature final sag at 100 ºC, calculate the final sag at 124.4 ºC). This calculation yields the results shown in Table C.2.

Table C.2—Example sag values with and without elevated creep

Temperature		Sag without elevated creep		Sag with elevated creep	
ºC	ºF	m	ft	m	ft
16	60	5.85	19.2	6.71	22.0
100	212	8.56	28.1	9.26	30.3
125	257	9.27	30.4	9.88	32.4
150	302	9.91	32.5	10.49	34.4

The examples presented here used creep predictor equations developed by Harvey and Larson (1970).