The Lifetime Estimate for ACSR Single-Stage Splice Connector Operating at Higher Temperatures

John Jy-An Wang, John K. Chan, and Joseph A. Graziano

***Abstract*—The power transmission conductor system consists of: the aluminum conductor, the steel-core supporting material, and the splice connector. The splice connector connects the aluminum conductor to form a continuing current transmission line. The splice connector region of a conductor system is more sensitive to material aging during service. This is due to the material discontinuity and the crimped connector's forming mechanism. The objective of this project is to develop a protocol to evaluate the integrity of a full tension single-stage splice connector (SSC) assembly operated at high temperature. The project focuses on thermal mechanical testing, thermal cycling simulation and the effective lifetime of the SSC system. The investigation indicates that thermal cycling temperature and frequency, conductor cable tension loading, and the compressive residual stress field within a SSC system have significant impact on SSC integrity and its associated effective lifetime. The developed governing equation and its application to assure the adequate service life of transmission lines are also discussed in the paper.**

***Index Terms*—Aluminum conductor steel reinforced (ACSR), compressive residual stress, high-temperature low sag conductors, single-stage splice connector, tensile splice connector, thermal cycling, transmission lines.**

I. Introduction

As A result of increasing power demands and the higher operating temperatures of transmission lines, there are concerns about the integrity of crimped-type splice connectors. These connectors play an important role in the efficiency and reliability of power transmission systems. The objective of this research is to develop an inelastic design methodology for the single-stage splice connector (SSC) of the aluminum conductor steel-reinforced (ACSR) conductors and to formulate time-dependent failure criteria that will ensure adequate service life of the ACSR SSC system. The implementation of the results from this research allows electric utilities to predict the service life of SSC of ACSR conductor systems related to the number of thermal cycles associated with operation during peak periods. The implementation of a methodology for predicting SSC service life can result in significant improvements in the transmission capacity of the electric grid and its reliability.

To gain a clearer understanding of SSC system design and functionality, a unique computer simulation protocol has been developed to identify potential failure mechanisms and to evaluate the long-term reliability of SSCs. The Phase I results of this project were presented in [1]. In Phase II of this project, efforts have been focused on 1) continuing the thermal-mechanical evaluation of materials used in conductors, including creep, isothermal fatigue, and the thermal-mechanical fatigue testing; 2) developing analytical simulation models to investigate the impact of SSC thermal aging, including thermal cycling and water quenching effects on the integrity of connectors; and 3) formulating governing equations to predict SSC performance and their service life at higher operating temperatures. The results of these Phase II efforts are presented in this paper.

II. Background

The compressive residual stress left in a crimped splice connector gives the clamping strength used to secure aluminum conductors. A significant relaxation of this initial residual stress occurs, especially at higher operating temperatures. A consequence of relaxation of the initial compressive stress field is the reduction of the connector's initial-rated tensile breaking strength (RBS). Therefore, the compressive residual stress in a crimped-type splice connector establishes the point of reference for predicting the effective life of a conductor system during service.

A. Temperature Profiles Within an SSC System

A series of thermal cycling experiments was carried out in the Haslet Laboratory of EPRI. They determined the temperature distribution profiles during thermal cycling inside the connector fitting of an ACSR Drake conductor system. Measurements were obtained from thermocouples (TCs) embedded within the SSC systems. The reference temperature corresponds to a location on the surface of the conductor about 5 m away from the connector fitting. These experiments revealed the following:

1) For a new system, the SSC surface temperature is lower than the power-line surface temperature.
2) The temperature at the steel core is normally higher than that of the aluminum wires, except at the core-grip region.
3) The SSC splice surface temperature is lower than that of the aluminum conductor wires underneath.
4) The temperatures of the SSC system increase continuously during thermal cycling; temperature gradients observed from the embedded TCs in the SCC system also change

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J. J.-A. Wang is with Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA (e-mail: wangja@ornl.gov).

J. K. Chan is with EPRI, Palo Alto, CA 94304 USA (e-mail: jchan@epri.com).

J. A. Graziano is with the Tennessee Valley Authority, Chattanooga, TN 37402 USA (e-mail: jagraziano@tva.gov).

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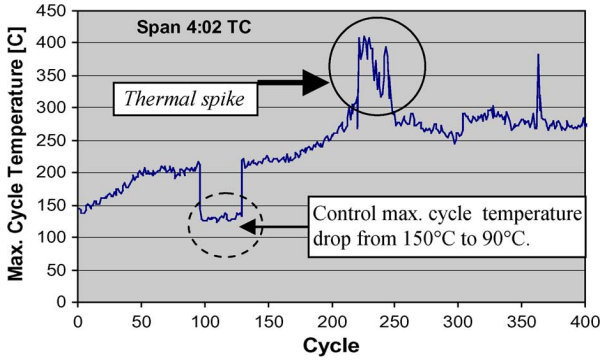

Fig. 1. Maximum cycle temperature history for quenched data.

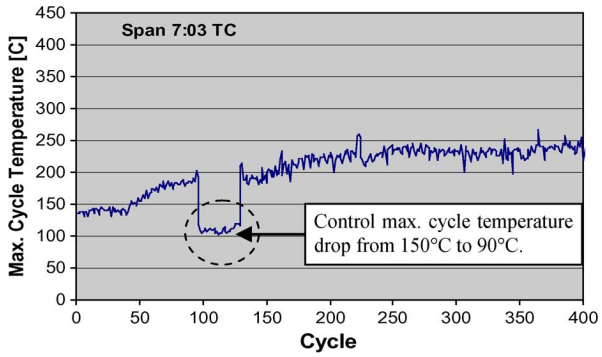

Fig. 2. Maximum cycle temperatures for nonquenched data.

with thermal cycling. The majority of SSC conductor temperatures became greater than the 150 °C reference temperature after about 50 cycles.

5) Significant temperature increases are due to increased SSC resistivity. This is a direct result of the thermal-cycle-induced reduction in compressive residual stresses in the SSC fitting and the buildup of an aluminum–oxide scale.
6) Water quench was applied once every 100 thermal cycles to one half of the eight testing spans. Significant thermal spike phenomena were observed on the quench span but not on the nonquench span. Figs. 1 and 2 present a comparison of quenched and nonquenched data, at the interface between the steel core and aluminum conductor.
7) A significant drop in tension loading was observed for four SSC spans, and some experienced a 70% reduction. This phenomenon indicates that the progressive slippage of the conductor wires occurred in the SSC system; this appears to be the result from loss of clamping compressive residual stresses in the SSC system due to thermal cycling.
8) The SSC temperature profiles obtained from thermal cycling experiments are used as temperature input for FEM thermal cycle simulations, where heatup sleeve surface temperatures are 70 °C, 100 °C, 125 °C, 150 °C, 175 °C, 225 °C, 250 °C, 275 °C, 290 °C, 315 °C, and 350 °C, and the cool-down temperature is 20 °C.

III. Thermal Mechanical Testing

Thermal mechanical tests, which include tensile, creep, fatigue testing, and thermal mechanical fatigue, were carried out on 1350-H19 (conductor), 3003-H183 (sleeve), and 6061-T6 (core-grip). Pertinent test information and results are summarized as follows.

- There is a significant decrease in strength at high temperatures, for instance, at 260 °C, the strength reductions are:
  - 1350-H19: 77%;
  - 3003-H183: 67%;
  - 6061-T6: 45%; w/ 10-h holding: 60%.
- In order to simulate the two thermal cycles per day for the power-line environment, the holding time for the tensile samples was set to 10 h at the target temperature.
- Thermal annealing has a significant impact on SSC component strength, as revealed with the decrease in the room-temperature tensile strength of annealed samples, especially for an annealing temperature greater than 200 °C. Effective annealing temperature ranges for SSC system components are set between 200 °C to 370 °C with a 10-h duration.
- The true stress-true plastic strain curves were determined by thermal mechanical testing of 1350-H19, 3003-H183, and 6061-T6 aluminum materials. This provides inelastic mechanical properties input for FEM analyses. The annealed data show a significant decrease in the yield and the associated stress-strain curves compared to the baseline data. Similar trends are shown for 3003-H183 and 6061-T6 aluminums.
- Creep tests for 1350-H19 aluminum were carried out at temperatures between 25 °C to 250 °C, and stressed between 2.5 ksi to 17.7 ksi (60 to 450 lbs.). Significantly higher creep rates were observed for test temperatures above 150 °C and tensile stresses greater than 6 ksi (150 lbs).
- The fatigue test results indicate that the effective fatigue life for SSC system materials is strongly dependent on the temperature and strain amplitude. Different aging responses were observed with room temperature and high-temperature fatigue tests, for 1350-H19, 3003-H183, and 6061-T6 aluminum.
- During thermal-mechanical fatigue (TMF) testing, the total strain (mechanical strain + thermal strain) is maintained near 0% with temperature cycles between 75 °C and 175 °C. The TMF testing results indicate that the associated material hardening induced by thermal cycling may be annealed by the testing temperatures during the alternating aging cycles and no obvious long-term TMF damage or fracture was observed from tested samples after some 9000 TMF cycles. In order to simulate the tension loading drop of a power line during a heat-up cycle, a series of TMF tests was also performed using variable "total strain" cycle ranges from 0% to 0.2% or 0.3%. No long-term aging degradation was observed from this type of TMF test.
- SEM postmortem examination of the fatigue samples obtained from SSC component materials revealed the typical striation representative of fatigue fracture with inhomogeneous textures that originated from cold-drawing mechanisms. The SEM images of fracture 1350-H19 samples are shown in Fig. 3.

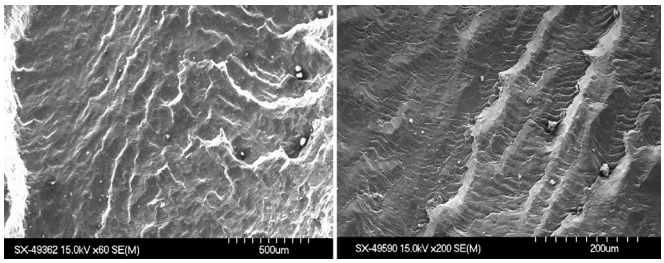

Fig. 3. SEM images of typical 1350-H19 fatigue fractured samples.

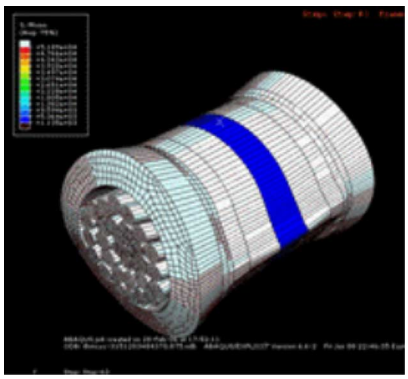

Fig. 4. SSC FEM model.

IV. SSC FEM Thermal Cycling Simulation

The FEM thermal cycle simulations for the SSC system were computed sequentially with (heatup) splice surface temperature ranges from 70 °C, 100 °C, 125 °C, 150 °C, 175 °C, 225 °C, 250 °C, 275 °C, 290 °C, 315 °C, and 350 °C, and with a cool-down temperature of 20 °C. Initially, there are three-iteration cycles for a targeted temperature range during simulation. Parameter studies for the tensile loading effect and the quench effect were also carried out. The center section of the FEM model was used for compressive residual stress relaxation studies of the ACSR Drake SSC system, as shown in shaded area of the crimped section in Fig. 4. In the FEM model, the right end of an ACSR Drake conductor, and its steel core, was fixed and no constraints were set for the left end of the ACSR conductor. In order to investigate the effect of tensile loading on SSC thermal cycling, two load conditions were considered: 1) tensile loading equivalent to 25% RBS and 2) without tensile loading. The temperature profiles obtained from thermal cycle experiments were incorporated into the FEM thermal cycling simulation.

The tensile load distributions between aluminum wires and steel-core wires used for FEM thermal cycle simulation are referred in tension data listed in Tables 2–4 of the Southwire Overhead Conductor Manual. These data were for a 600-ft span ACSR Drake conductor cable under heavy load conditions [2]. At a knee point of 100 °C, the steel-core wires will carry the entire cable tensile load. The tensile stress distributions for steel and aluminum wires of a 600-ft span Drake conductor are shown in Table I.

TABLE I
Stress Distribution for 600-ft Span Drake Conductor

	Tensile Stress [psi]	
Temp.	Steel	Al.
20°C	33,340	7,147
45°C	31,422	4,197
70°C	29,504	1,247
≥100°C	31,875	0

A. Tensile Load Transfer Within a Drake Conductor SSC

To prevent the pull-out failure of an SSC fitting, the sum of the friction shear resistance forces from the "core-grip" and "conductor" sections needs to be greater than the tensile load transferred from the Drake conductor. The Phase I study [1] shows that the baseline SSC system had sufficiently high compressive residual stress to confine the conductor wires to the SSC system during an ANSI C119.4 Class 1 test. It is expected that the friction force resistance will decrease progressively during power-line operation. Therefore, the degradation of shear resistance forces provides the basis for an accurate estimation of the connector lifetime.

FEM thermal-cycle simulation results show different temperature sensitivities between core-grip and conductor sections. In the SSC system, the conductor section shows a significant reduction in compressive stress when the thermal cycle temperature reaches 125 °C, but the core-grip section still has significant compressive strength at temperatures up to 200 °C.

The FEM thermal cycle simulation was initially developed based on "multiple iterations per target temperature" approach. The FEM results indicate that the compressive clamping stress will continuously decrease during multiple iteration cycles for one target temperature. The reduction of compressive stress will result in increasing resistivity of the SSC system; this results in an increase of SSC system temperature. In reality, the follow-on iteration cycle will not maintain the same target temperature as that of the earlier iteration cycle, except for the reduction of the electric current. This phenomenon was also observed with the continuing increase of the conductor interface temperature from thermal cycling experiments. Indeed, data obtained from the multi-iterations algorithm further validate the effect of thermal cycling. However, this algorithm will result in overly conservative estimates for the SSC effective lifetime. It is noted that the simulation result of the conductor section seems to be very sensitive to the multi-iteration algorithm, while the core-grip section does not, except for cool-down data at a higher temperature (above 250 °C). Based on these observations, a "single cycle iteration per target temperature" algorithm was adopted to reproduce the simulation result for the conductor and the core-grip sections. These FEM simulation results were further used in SSC effective lifetime estimates.

B. Thermal Cycle Simulation for the SSC Conductor Section

The FEM simulation was performed by utilizing a 3-D dynamic/inelastic model with a "general contact" algorithm. A material property table for SSC components was created to serve as an input for FEM analyses. This contains four major parameters: 1) temperature, 2) material strength (yield, Young's modulus, etc.), 3) material threshold for heat-up or cool-down

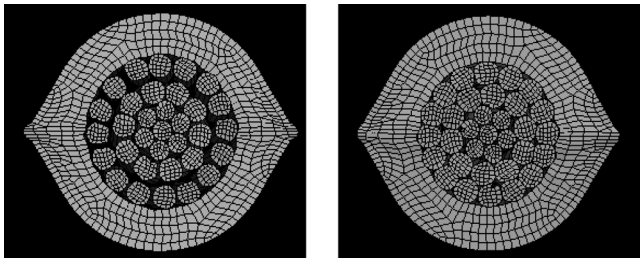

Fig. 5. FEM thermal cycle simulation (left) at 225 °C cycle range with tensile loading (right) at 315 °C cycle range no tensile loading.

cycle, and 4) inelastic stress-strain curves. The 10-h holding-time stress-strain curves were used in the FEM thermal cycle simulation investigation as follows.

- Simulation without tensile loading shows no significant reduction in compressive residual strength at cool-down/ambient and heat-up temperatures, until 250 °C. The FEM results with tension show significant voids or gaps, while the closed pack formation of the baseline conductor wires largely remain intact for a no-tension simulation, even at the 315 °C thermal cycle range, as shown in Fig. 5.
- Significant movement of the conductor wire and steel-core wires was revealed by thermal cycle simulation with tensile loading; this phenomenon was not predicted by thermal cycling simulation without tensile loading. This is a direct indication that the SSC system has lost its clamping strength and conductor slip has occurred.
- The simulation with tensile loading or/and quench shows severe reductions in the magnitude of SSC compressive clamping stress, during heat-up and cool-down cycles. At or above the thermal cycle range of 100–125 °C, a 92–95% reduction in compressive residual stress was reached. The FEM results with quench and tension at a 225 °C thermal cycle indicate that the majority of conductor wires have lost contacts with each other and with the SSC sleeve.
- The compressive force exerted onto the aluminum conductor boundary during heat-up and cool-down cycles is shown in Figs. 6 and 7, respectively. Significant relaxation of the compressive force in SSC was observed from heat-up and cool-down cycles. The quench plus tension case appears to be consistent with that of the full tension case. However, quenched data show a much higher reduction in compressive force at 125 °C than at full tension data. The half-tension (12% RBS) and half-tension plus quench cases show similar behavior compared to the full tension case.

C. Thermal Cycle Simulation for Core-Grip Section

The 2-D plane stress quasistatic/inelastic model with a "contact pairs" algorithm was used for thermal cycle simulation. The axial tensile loading of the core-grip section was simulated with lateral contraction of steel-core wire at the corresponding tensile loading and temperature. The FEM simulation indicates that the contact area between the core grip and the steel core is quite limited, as shown in Fig. 8. The FEM simulation indicates that the compressive force around the steel core decreases continuously

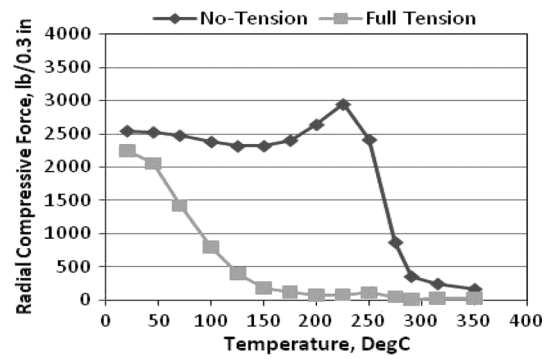

Fig. 6. Compressive force in the conductor section at heat up.

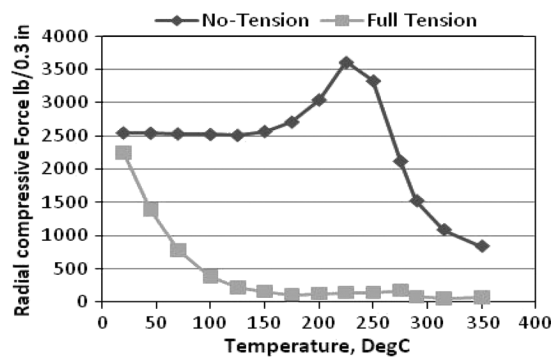

Fig. 7. Compressive force in conductor section at cool down.

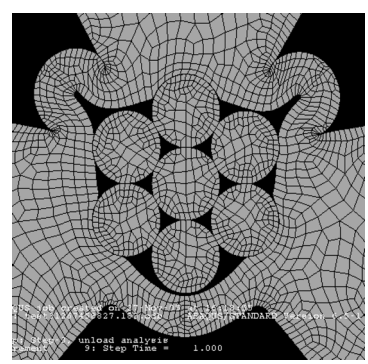

Fig. 8. Contacts within a core-grip section of an SSC system.

during thermal cycling. The discussions of FEM simulation results are described as follows.

- No significant different trend in the compressive residual stress was found from FEM results with tension or without tension, but different trends were observed between compressive force relaxation at heat-up and cool down cycles (as illustrated in Figs. 9 and 10, where the cool-down/room-temperature compressive force is relaxed much slower than the counterpart at the heat-up cycle at the targeted temperatures). Based on this finding, it appears that the current ANSI requirement of using room temperature tensile testing for evaluating the SSC reliability after thermal cycling might need to be modified to incorporate the tensile testing at the heat-up cycle of the targeted thermal cycling temperature.

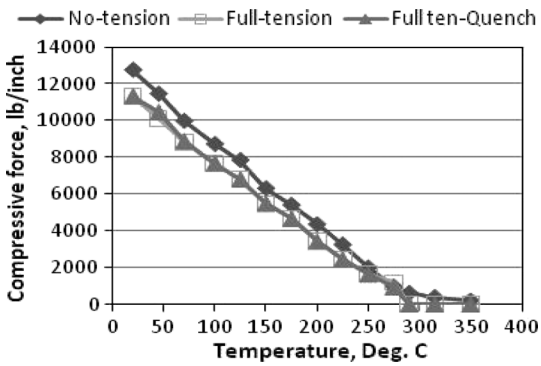

Fig. 9. Compressive force around steel core at heat up.

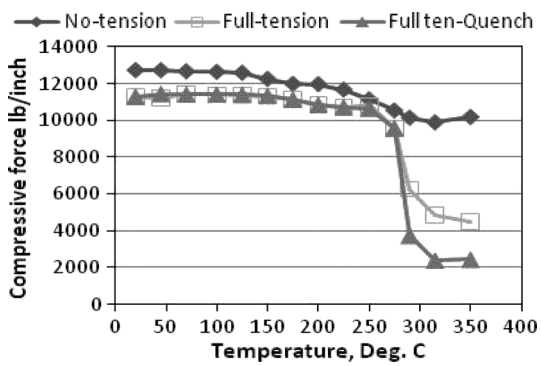

Fig. 10. Compressive force around steel core at cool down.

- The compressive clamping forces on the core-grip section decrease much less than that of the conductor section during thermal cycling. For instance, under full tension during the 150 °C heat-up cycle, the compressive force on the conductor section is reduced by about 96%, while the core-grip section still has about 50% compressive force left. The rapid decrease of compressive force on the conductor section in the early thermal cycle stage, from 20°C to 125°C means that the SSC system will have a relatively sharp increase in temperature and then approach a quasi-steady state. This is consistent with that observed from the experimentally determined thermal cycle temperature profiles. It is noted here that the core-grip section lost its compressive force completely at about the 300 °C heat-up cycle.

V. SSC Effective Lifetime Estimate

Accelerated connector aging can be attributed to connector component material aging. This includes creep, fatigue, TMF, aluminum–oxide film buildup, and microstructure evolution at the interfaces within the connector system [3]–[6]. This Phase II study further verifies that significant degradation of connector compressive residual stresses will occur during service, especially at higher operating temperatures. The consequences of degradation of the compressive stress field are an increase of SSC system resistivity and the reduction of SSC tensile strength. Therefore, the compressive residual stress within SSC can serve as a good indicator to predict the effective lifetime of an SSC conductor system during service.

Based on extensive thermal mechanical test results for SSC components, we have drawn the following conclusions:

- Creep data show low creep strain at a relatively low temperature ($\sim 70°$C) and medium loading for SCC aluminum materials. For conductors at temperatures above the knee point (100°C), aluminum conductor wires will relax and have zero tensile loading, and the associated long-term creep strain is negligible due to the lack of axial tensile loading.
- Due to relatively constant conductor cable axial loading, the associated fatigue damage to the SSC system is considered secondary. Based on thermal-mechanical fatigue data, the TMF-associated strain hardening was balanced by thermal annealing. Thus, no net TMF-induced aging damage occurred in the conductor materials.

The aging issues associated with material creep, and fatigue and TMF can be ruled out for the effective lifetime of the SSC system operating at high temperatures.

A. General Formulation for the SSC Lifetime Estimate

Based on thermal cycle simulation results, we observed that the conductor section acts as a temperature driver that dictates the SSC system temperature. The core-grip section is the main driver that secures the conductor cable at a higher operating temperature (above 100°C).

In general, there are three main subjects that need to be addressed while investigating the effective lifetime of an SSC system, namely, geometry constraint integrity, cable tension effect, and SSC system materials degradation. By analyzing thermal mechanical testing, we have ruled out the influence of material degradation associated with creep deformation or fatigue at high operating temperatures. Moreover, from the degradation rate point, the impact of losing the geometry constraint (such as void density increase and decrease of compressive residual stresses) seems to be a more severe impact on the SSC effective lifetime than aluminum–oxide build up—with regard to the SSC system temperature increase. Therefore, in the SSC effective lifetime investigation, we will focus on the subjects of tensile effect and the degradation of geometric constraints.

In order to put thermal-cycle simulation results into practical use to predict the service lifetime of SSCs, we need to establish a relationship between the time-dependent SSC-splice surface temperature and the associated effective constraint strength remaining in the SSC system to secure the conductor cable. The SSC's splice surface temperature can be easily monitored with a remote sensor. Therefore, it could be possible for the splice surface temperature to provide a direct link to the operation-time and operation-temperature history.

B. Calculation of the Shear Resistance Force in SSCs

In order to relate the SSC compressive stress to the effective shear resistance force against the pullout of the conductor cable during service, the temperature-dependent friction coefficient needs to be considered. The friction coefficients of steel versus aluminum (Al) for the core-grip section are listed in Table II, based on [7] and [8].

TABLE II
TEMPERATURE-DEPENDENT FRICTION COEFFICIENTS OF STEEL & Al

Temperature (°C)	22	35	93	148	211	260	315	371
Friction Coefficient, μ	0.610	0.545	0.259	0.115	0.064	0.047	0.035	0.020

TABLE III
TEMPERATURE-DEPENDENT FRICTION COEFFICIENTS OF Al AND Al

Temperature (°C)	25	100	150	177	205	230	260	315
Friction Coefficient, μ	1.000	0.875	0.750	0.625	0.542	0.333	0.167	0.120

TABLE IV
AMBIENT TEMPERATURE FRICTION COEFFICIENTS OF STEEL AND Al

Aging Temperature (°C)	20	175	200	225	250	275	350
Friction Coefficient, μ	0.610	0.610	0.580	0.549	0.427	0.366	0.366

TABLE V
AMBIENT TEMPERATURE FRICTION COEFFICIENTS OF Al AND Al

Aging Temperature (°C)	25	175	200	225	260	315	350
Friction Coefficient, μ	1.000	0.950	0.860	0.630	0.180	0.160	0.16

The room temperature static friction coefficient 1.0, Al versus Al, was chosen for a crimped SSC [8]. In general, the friction coefficient varies linearly with tensile strength [9]. The trend of yield stress for 1350-H19 aluminum was used for estimating the friction coefficients of Al versus Al for the conduction section. The estimated friction coefficient is listed in Table III.

Due to significant annealing of SSC aluminum components observed at high temperatures, the friction coefficients at ambient temperature (cool down) after the thermal cycling need to be modified (according to the tensile yield reduction ratio). At above 250 °C, the tensile yield stress of SSC aluminum starts to decrease significantly. The Al versus Al friction coefficient correction was based on the ratio of thermal cycling aging yield stress to that of baseline tensile yield stress, at ambient temperature. Regarding the friction coefficient of steel versus Al, a similar approach was used to estimate the ambient temperature friction coefficient but with a smaller reduction ratio. This is because steel strength largely remains intact at the temperatures of interest; furthermore, a very rough interface exists between the core grip and the steel core. The estimated ambient-temperature friction coefficients at high-temperature thermal cycle ranges are provided in Tables IV and V for steel versus Al, and Al versus Al, respectively.

The shear resistance forces, for the full tension loading case, are evaluated during heat-up and cool-down cycles, for core-grip and conductor sections, respectively. The calculated shear resistance forces and fitting curves for heat-up cycles are shown in Fig. 11. It clearly indicates the temperature dependence of SSC shear resistance capacity. Here, the shear resistance decreases exponentially with temperature increases. The shear resistance force calculated from the "quench plus full-tension" case appears to be very close to that of the full-tension case. There are differences among quench and nonquench data at high temperatures for the core-grip section during the cool-down cycle, as shown in Fig. 10. However, due to the diminished friction coefficient of steel and aluminum at temperatures above 250°C, the difference of the resulting shear forces between full tension, and quench plus full tension cases is very small. Thus, only the full tension simulation data were used to develop the effective lifetime prediction models for the SSC system.

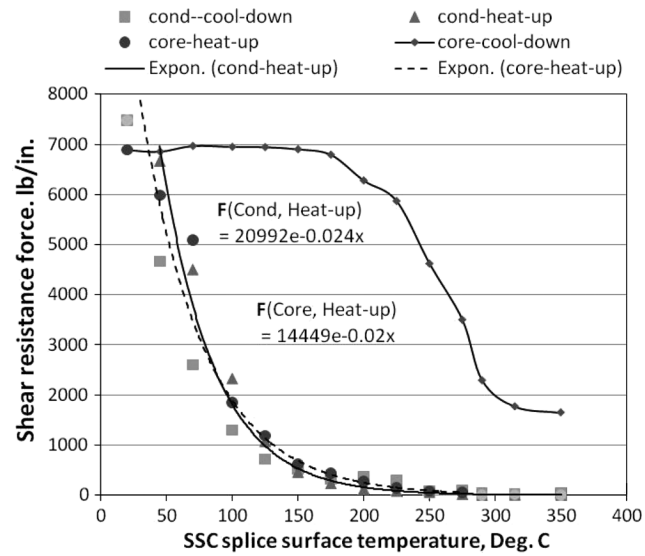

Fig. 11. Temperature-dependent shear resistance trends for the SSC Drake conductor system.

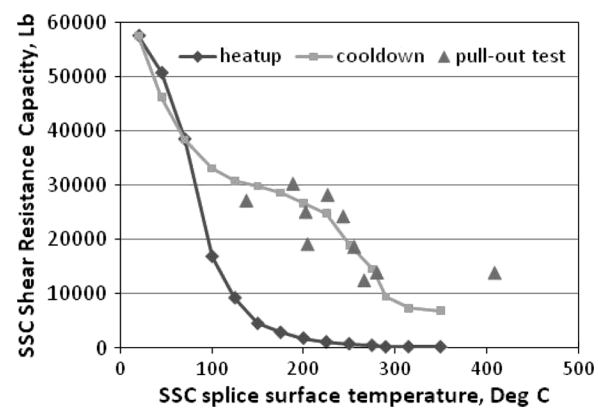

Fig. 12. Shear resistance capacity of the ACSR Drake SSC system with 16-in long net core-grip and conductor sections.

Fig. 12 shows shear resistance capacity of an ACSR Drake SSC splice with 16-in net length (combined conductor and core-grip sections). The ambient temperature post thermal cycle pull-out tests for Drake SSC fitting were also carried out. The test results are also shown in Fig. 12. With regard to the craftsmanship of forming the SSC fitting and other uncertainties involved in the thermal cycling testing, the predicted values fit remarkably well to that of the pullout test results.

C. SSC Effective Lifetime Predictions

1) Governing Equation of SSC Shear Resistance Capacity: The sole function of an SSC system is to connect and secure the conductor cable during power transmission. Therefore, the SSC must have sufficient shear resistance capacity to retain the aluminum conductor cable at any operating temperature and loading condition. The governing equation for the SSC lifetime

prediction, with operating temperatures $\geq 45°$C, can be written as below:

For the heat-up cycle

$$R_h = F_{cond}(T, heat-up) * L_{cond} + F_{core}(T, heat-up) * L_{core}.$$

For the cool-down (RT) cycle

$$R_c = F_{cond}(T, RT) * L_{cond} + F_{core}(T, RT) * L_{core}.$$

The effective SSC shear resistance capacity can be written as

$$\begin{aligned} R_{SR} &= minimum(R_h, R_c,) = R_h \\ &= 20992 * e^{-0.024T} * L_{cond} \\ &\quad + 14449 * e^{-0.02T} * L_{core} \end{aligned} \tag{1}$$

where F is the governing equation of the temperature-dependent shear resistance force, as stated in Fig. 11, and the subscripts "cond" and "core" stand for the conductor and core-grip sections, respectively. T is the maximum temperature per cycle at the SSC splice surface, and L is the effective length. R_h and R_c are the shear resistance capacities during heat-up and cool-down cycles, respectively. R_{SR} is the effective shear resistance capacity provided by the SSC system.

For safe operation, R_{SR} must be greater than the tensile loading of the ACSR conductor system and its associated environment at any temperature. Thus, the end of life of an SSC system can be defined as when the tensile loading of a power transmission line is approaching the shear resistance capacity of the SSC system. From a design point, the SSC shear resistance capacity is dictated by the effective length of the core-grip and conductor sections. Thus, to ensure safe operation of power transmission lines at target service temperatures with the designated cable loading, the designed SSC system must have a sufficient length of core-grip and conductor sections to provide enough safety margin.

A 600-ft-span Drake conductor system, under heavy loading conditions (see [2, Tables 2–4]), was used to demonstrate the general applicability of this new method for investigating the SSC effective lifetime. For a conservative example, the initial tension loading listed in [2, Tables 2–4] was used in this demonstration. No tensile loading data were available from [2, Tables 2–4] for a cable temperatures of greater that 100 °C. So, the Catenary cable theory was used to estimate conductor tensile loading at higher temperatures. The calculated tension loading was then normalized with [2, Tables 2–4] tension loading at 100 °C from [2]. A series of temperature-dependent SSC shear resistance capacities was generated for SSC systems with net (conductor + core-grip) lengths of 12, 16, 20, 24, and 40 in, respectively, with the assumption of equal length for the conductor and the core-grip sections. The result indicates that SSC systems, with initial 25% RBS tension loading, has sufficiently high shear resistance capacity to secure the conductor cable at SSC surface temperatures below 100 °C. A detailed view of the shear resistance capacities for less than 5 000 lbs. are shown in Fig. 13. Fig. 13 also shows that a 12-in-long SSC splice system, formed by an ALCOA 60 ton 12CD die, will probably fail at an SSC surface temperature of greater than 150 °C. For a 40-in-long splice,

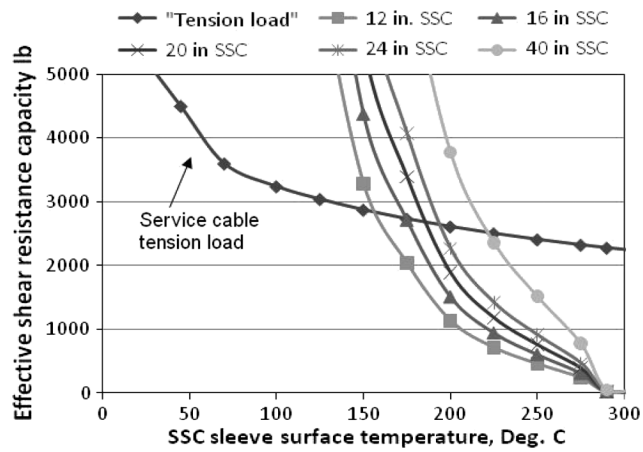

Fig. 13. Drake SSC shear resistance capacity at high temperature.

it will extend the SSC system operating temperature to 225 °C. This exercise shows that the current SSC system will function well with an SSC splice surface temperature below 100 °C or up to 125 °C $\sim$ 150 °C for emergency situations. However, the shear resistance capacity of the current SSC system apparently is not an efficient design for high-temperature operation.

2) Governing Equation of SSC Surface Temperature History: Time-frequency-dependent SSC surface temperatures are measured during thermal cycle experiments. Here, the ACSR Drake conductor operation temperature was controlled to 150 °C, except for the cycles between 97 to 129, where the conductor temperature was controlled to 90 °C. Some representative SSC surface temperature history data are used to develop governing equations that relate SSC surface temperature to the thermal cycle frequency (or time history).

Due to significant drops in tension during SSC thermal cycling experiments, the tested spans were retensioned at the following cycle numbers: 120, 407, 611, 858, 974, or whenever the aging SSC fitting was replaced with a new SSC fitting. The tension history data of the four SSC tested spans show that the conductor tension load decreases continuously during thermal cycling. This is a direct indication of conductor slippage in an aging SSC system. Re-tensioning SSC spans back to 20% RBS ($\sim$6200 lbs.) will introduce relatively large slippage jumps, and through slippage, it will expose fresh (good) contact surfaces at SSC system interfaces. This will reduce the resistivity of aging SSC; and result in a decrease of SSC surface temperatures. Normally, the increase of SSC surface temperatures will resume right after restarting thermal cycling. Large temperature data scatter, resulting from SSC forming quality and thermal cycling experiments, seems to also depend on the test span and SSC sequential position within the test span (normally, one test span contains five SSC splices, including two SSC dead-end splices).

The re-tensioning and the replacement of SSC fittings during thermal cycle testing may further complicate the effort to develop trend curves for frequency-dependent SSC surface temperatures. Nevertheless, SSC surface-temperature history data show that SSC aged quickly within the first 100 cycles and then approached steady-state temperature. Steady-state surface temperatures of a normal operating SSC are around 160 °C to 200 °C, and around 160 °C to 220 °C for some quenched data. In

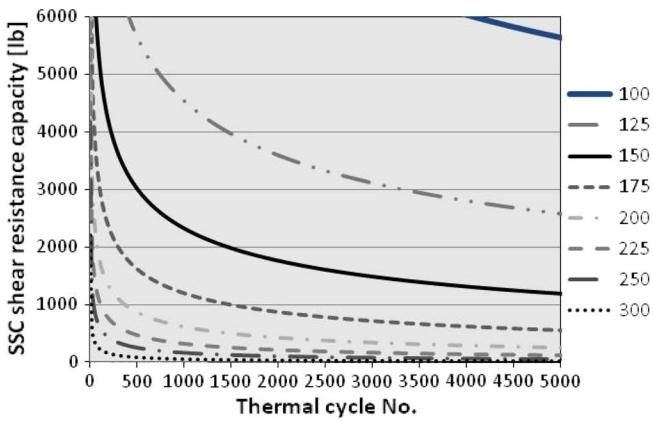

Fig. 14. ACSR Drake SSC lifetime for shear capacity <6000 lbs.

order to extend the trend curve to a wide spectrum of conductor operating temperatures, one assumption was made—the general trend of the governing equation remains the same and varies linearly with different conductor operation temperatures. According to this methodology, a framework of SSC surface temperature–frequency history chart, which is a function of conductor operation temperatures, was developed. Based on the above and the temperature data, which contains data up to first re-tensioning (less than 400 cycles), a governing equation of frequency-dependency SSC surface temperature T was developed and described

$$T = 0.6375 * T_{cond} * N_f^{0.0969} \tag{2}$$

where T_{cond} is the control conductor temperature and N_f is the number of cycles (frequency). By combining (1) and (2), the overall governing equation for the SSC effective lifetime can be written as

$$\begin{aligned} R_{SR} &= 20992 * e^{-0.024T} * L_{cond} \\ &\quad + 14449 * e^{-0.02T} * L_{core} \\ &= 20992 * exp\left(-0.024 * 0.6375 * T_{cond} * N_f^{0.0969}\right) \\ &\quad * L_{cond} + 14449 \\ &\quad * exp\left(-0.02 * 0.6375 * T_{cond} * N_f^{0.0969}\right) \\ &\quad * L_{core} \end{aligned} \tag{3}$$

3) Demonstration of SSC Effective Lifetime Prediction: A half section of an ACSR Drake conductor SSC fitting has a 4.5-in-long core-grip section and about a 4.5-in-long conductor section. With the consideration of the taper sleeve ends and the conservative point, the net length for the core-grip section and the conductor section are estimated at 4 in each. The associated SSC effective lifetime trends for shear capacities below 6000 lbs. and the conductor operating temperatures in the ranges of 100 °C to 300 °C are illustrated in Fig. 14. The service conductor cable tension loads for a 600-ft span Drake conductor system, under heavy loading conditions, are shown in Fig. 13. From Fig. 13, for conductors operating at 125 °C, the required service tension load is 3040 lbs. Based on this screen criterion and Fig. 14, a conductor operating at 125 °C, the SSC system can meet the screening criterion of a 3040-lb. tension load for up to 3100 cycles. For a 150 °C conductor operating temperature, the screening criterion is a tension load of 2873 lbs. At about 550 cycles, the SSC shear resistance capacity is about 2922 lbs., which is slightly larger than the required service tension load of 2873 lbs., shown in Fig. 13.

VI. Conclusion

The integrity of SSC systems under thermal cycling at high operating temperature has been analyzed in a project funded by EPRI at Oak Ridge National Laboratory. The results of FEM simulations for the SSC forming mechanism and SSC aging induced by thermal cycling were found to be in good agreement with residual stress measurements obtained by neutron diffraction techniques and SSC aging/degradation trends obtained from the thermal cycling experiments of SSC Drake conductor systems. A finite-element simulation protocol was also developed to provide guidance in estimating the effective lifetime of SSC system performance. The main findings are as follows.

- Compressive residual stress fields and the associated shear resistance capacity within an SSC system can serve as a good index for the effective lifetime estimate.
- Thermal cycling has a significant detrimental effect on SSC lifetime, especially under high-temperature operation.
- Tensile loading needs to be considered in the SSC lifetime investigation, especially when in combination with dynamic tension loading.
- Both the compressive residual stresses at cool-down and at heat-up cycle temperatures need to be considered when evaluating SSC system performance and lifetime.
- It is expected that the developed protocol and the associated SSC life prediction models can be very beneficial to the power grid and power transmission-line operators as well as the conductor system designer since this protocol will enhance safe operations needed to meet the current power demand.

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John Jy-An Wang received the Ph.D. degree in mechanics of material and structural dynamics from the University of California, Berkeley, in 1988.

Currently, is a Senior Research Staff Member at the Oak Ridge National Laboratory (ORNL), Oak Ridge, TN. Since 1989, he has been with ORNL and published many technical reports and journal articles on subjects related to fracture toughness evaluation, nonlinear material behavior characterization, material damage modeling, the neutron radiation embrittlement predictions, and the inventor of the spiral notch torsion fracture toughness test.

Dr. Wang is a committee member of ASTM E10 and of ASME PVP. He has a P.E. license in the structure and mechanical engineering.

John K. Chan received the B.Sc. degree in electrical engineering and M.Sc. degree in mechanical engineering from the University of Manitoba, Winnipeg, MB, Canada, in 1971 and 1975, respectively.

He was with Manitoba Hydro from 1973 to 2003. He was the Head of Transmission Line designs before he left Manitoba Hydro for the Electric Power Research Institute. Currently, he is Manager of the increased power-flow program under the power delivery and market sector of the Electric Power Research Institute, Palo Alto, CA.

Joseph A. Graziano received the Ph.D. degree in civil engineering from the University of Tennessee, Knoxville.

He is a Senior Program Manager with the Tennessee Valley Authority (TVA), Chattanooga, TN. He began his career with Westinghouse Electric, General Electric, Teledyne Continental Motors, Babcock, and Wilcox before joining the TVA Nuclear Power Department. He is a registered professional engineer in the State of Tennessee.