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**KINECTRICS NORTH AMERICA INC. TEST REPORT
FOR 3M COMPANY TO DETERMINE THE SAG – TEMPERATURE – TENSION
PERFORMANCE OF 675TW 3M BRAND COMPOSITE CONDUCTOR**

**Kinectrics North America Inc. Report No.: K-422008-RC-0001-R01
June 23, 2005**

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INTRODUCTION

A Sag – Temperature – Tension Test was performed for 3M Company on their 3M Brand Composite Conductor, which is also known as Aluminium Conductor Composite Reinforced (ACCR) Conductor. This test is part of a larger series of tests to demonstrate the viability of ACCR conductors for use on overhead electric power transmission lines. The tests were performed by Kinectrics North America Inc. personnel at 800 Kipling Avenue, Toronto, Ontario, M8Z 6C4, Canada. . 3M Company owns all data and copyright to this information and are publicly released by 3M.

A sag-tension-temperature study on 675TW showed a knee-point transition in the range of 80-100°C. The “compressive stress parameter” or “built-in tensile stress parameter” should be set at –1.45 ksi (-10MPa) for the line design software programs. The line design software programs such as Alcoa Sag10 and STESS predict the sag-tension-temperature behaviour very well.

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TEST OBJECTIVE

The objective of the Sag – Temperature – Tension Test was to determine the sag and tension of the 675TW kcmil ACCR conductor when subjected to increasing temperatures. The composite core of 3M's ACCR conductors has a lower coefficient of thermal expansion and higher conductivity than the steel core in conventional ACSR conductors. The Sag – Temperature – Tension Test tests would provide information on whether these differences affect the thermal and physical response of the ACCR conductors.

TEST CONDUCTOR

The conductor tested was designated ACCR/675TW, 20/7 manufactured by 3M Company. The construction of this conductor has 20 aluminum alloy wires in 2 layers surrounding seven core wires. The outside diameter of the conductor is 22.91mm (0.902 inches).

The data sheet on the 675TW kcmil ACCR conductor used in the sag – temperature – tension test is contained in Appendix A.

Sixty-eight (68) meters of the conductor was prepared. The conductor was terminated as shown in Figure 1. Each end of the conductor was passed through aluminum housings. The conductor strands were splayed apart within a cone-shaped cavity inside the aluminum housing. High-temperature epoxy resin was poured into the cavity to “lock” all strands of the conductor together. The strands were reformed outboard of the aluminum housing and a compression terminal was compressed on the end of the conductor to allow current to be passed through the sample.

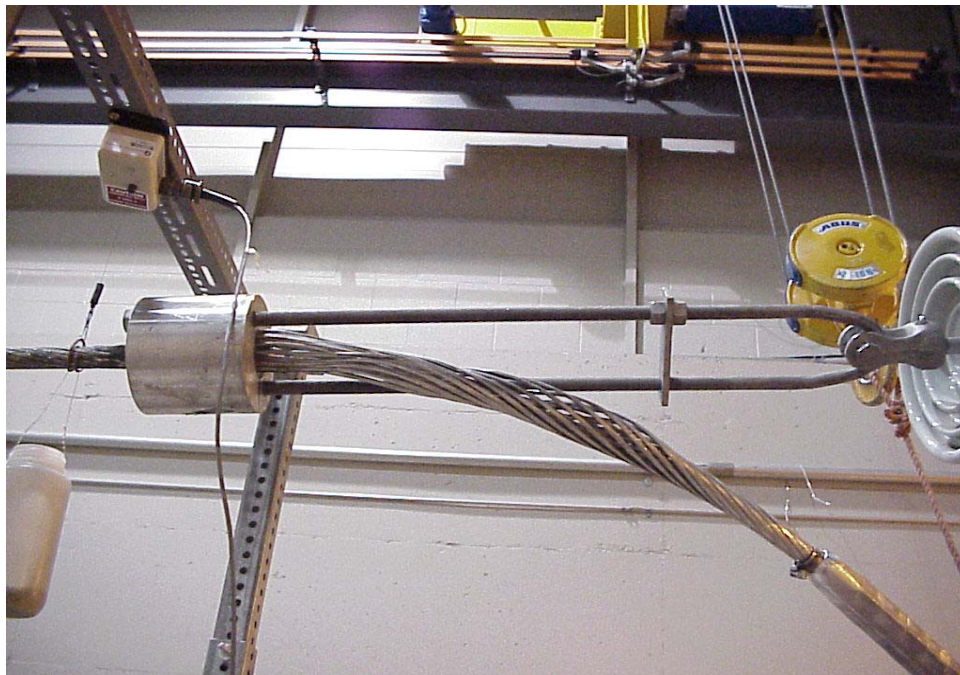


Figure 1 Epoxy dead-end

TEST SET-UP

Test Apparatus

The Sag – Temperature – Tension Test was carried out at Kinectrics' Conductor Dynamics Laboratory. The laboratory is temperature controlled to $22^{\circ}\text{C} \pm 2^{\circ}\text{C}$ with minimal air movement. A schematic of the setup is shown in Figure 2. The maximum span length (ie. tension eye to tension eye) was 68.8 m. The actual conductor length was shorter than this to accommodate end hardware such as the tensioning dead-ends, insulators, load cells and other links. The sample was tensioned horizontally about 2.44m (8 feet) above the ground.

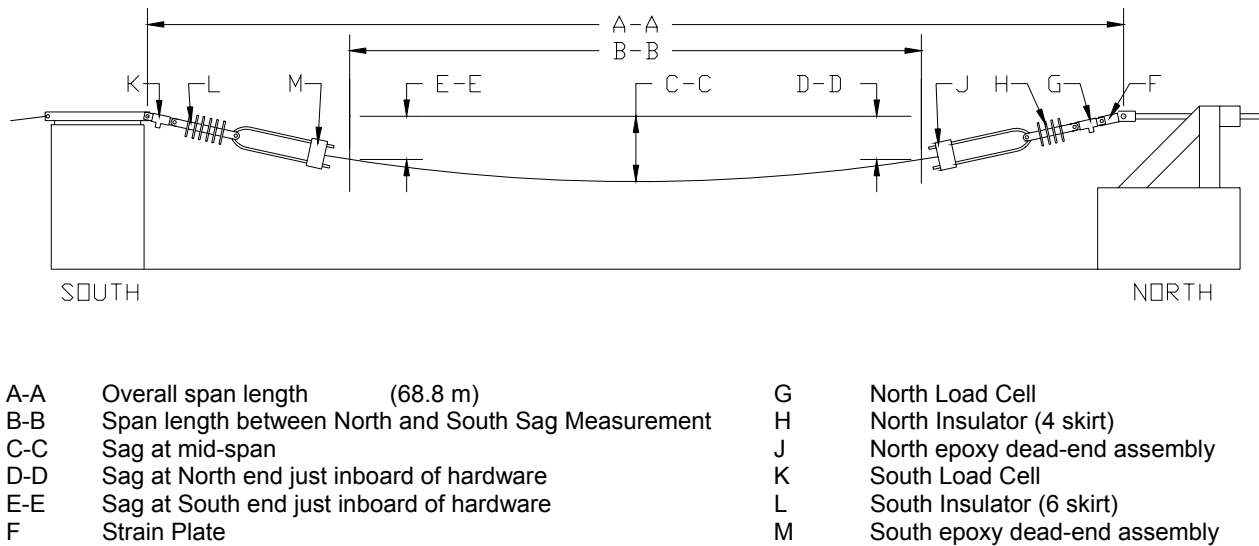


Figure 2 Schematic of Test Setup

A current transformer provided the circulating current to heat the cable. One end of the conductor was connected to a tap of the current transformer. The opposite end of the conductor was connected to a 795 kcmil ACSR conductor, (return conductor) to complete the circuit back to the current transformer. The 795 kcmil ACSR conductor was tensioned at the same level and 1m away from the test conductor. The test conductor and the return conductor are shown in Figure 4.

Instrumentation

Conductor Tension

A strain gauge load cell measured the tension in each conductor during the test. The load cell was installed between the insulator and the dead-end structure so that it would be electrically isolated from the conductor. The signal from the load cells were amplified by optically isolated signal conditioners to provide a 0 to 5 volt signal for the data acquisition system.

Conductor Temperature

The temperature of the conductor was measured at two(2) locations using thermocouples. One location was at the centre of the span the other location was at halfway between the centre and one dead-end ($\frac{1}{4}$ point). The core, middle aluminum layer, and outer aluminum layer were measured at each location. The following summarizes the thermocouple positions at each location.

Thermocouple #1 – Next to the core

Thermocouple #2 – Between two aluminum-alloy wires in the middle layer

Thermocouple #3 – Between two aluminum-alloy wires in the outer layer

The thermocouples were optically isolated from other instrumentation to prevent electrical interference into the data acquisition system.

A typical thermocouple installation is shown in Figure 3.

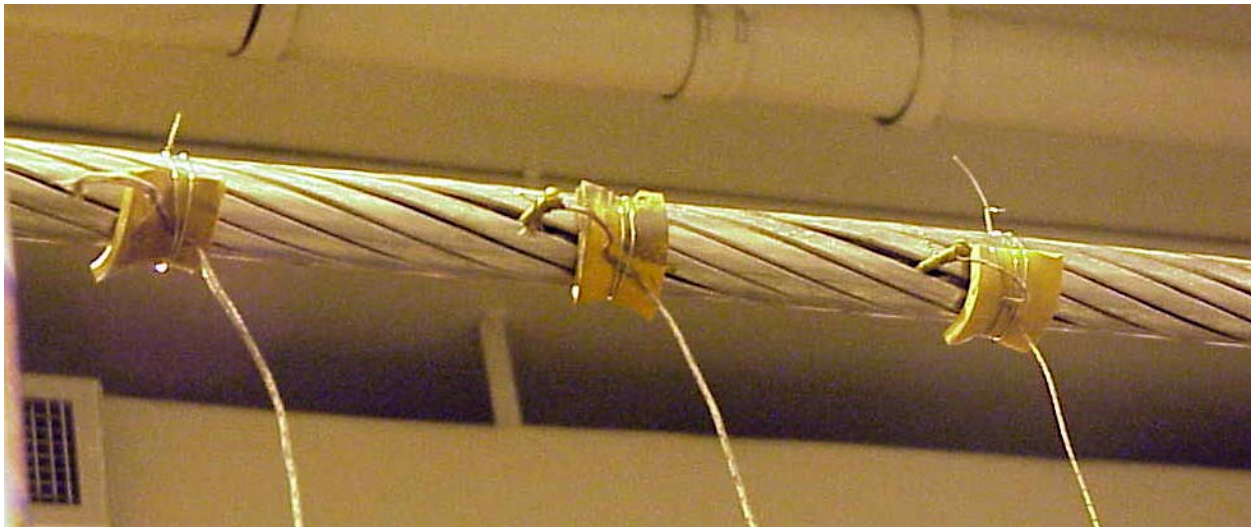


Figure 3 Typical Thermocouple Installation

Conductor Sag

The ends of the conductor were not fixed in space during the heating and cooling because the conductor end fittings were part of the tensioned span. It was therefore necessary to measure the vertical and longitudinal position at both ends of the conductor as well the vertical position at midspan. Pull wire potentiometers were used to make these measurements for each conductor.

For the vertical measurements, the potentiometer housings were mounted on fixed supports above the conductors. The pull wire was attached to the conductor and would extend from the housing as the sag increased when the conductor was heated and would retract into the housing as the sag decreased when the conductor cooled. Three (3) potentiometers were located at three (3) positions along the conductor, one at midspan and one at each end of the span.

For the longitudinal measurements, the potentiometers were mounted on fixed supports located outboard of the end fitting attachment points. The pull wire was attached to the conductor and would extend from the housing as the sag decreased when the conductor was cooled and would retract into the housing as the sag increased when the conductor was heated. Two (2) potentiometers were located at each end of the span. This setup is shown in Figure 4.



Figure 4 Test Setup Near Dead-end

Data Acquisition and Control

A Labview-based data logging system recorded all temperatures, sag or clearance and tension data. The system sampled every 2 seconds and saved data at a user-selected interval. The data was saved every 5 seconds when the change in sag-temperature was greater, and slowed to every 30 seconds when the conductors were at steady-state temperature.

The data acquisition system also provided a 5-volt logic control signal that controlled a Silicon Controlled Rectifier (SCR) through an optically isolated output module. The data acquisition system would turn current on or off based on the thermocouple readings. Conductor temperature was considered to be the independent variable.

TEST PROCEDURE

The current transformers were turned "ON" and left "ON" until the test conductor reached the target temperature of 240°C. The whole conductor was considered to have reached this temperature as soon as the highest reading thermocouple measured 240°C. The current was then turned "OFF" and the conductors were allowed to cool by natural convection to room

temperature. Two (2) cycles were performed using this procedure. The details of the two cycles are listed in Table 1.

Table 1 Summary of Test Parameters

Parameter	First cycle	Second Cycle
Max Temp. of ACCR/675TW	240°C	239°C
Temperature rise from ambient (23°C)	217°C	216°C
Temp. rise time	23 minutes	43 minutes
Average heating rate	9.5°C/min	5.1°C/min
Cooling time 240°C to 30°C	1 hour 10 minutes	1 hour 12 minutes
Average cooling rate 240°C to 30°C	3.0°/min	2.9°/min
Cooling time 240° to ambient (23°C)	n/a	3 hours 41 minutes
Average cooling rate 240°C to ambient (23°C)	n/a	1.0°/min

TEST RESULTS

A plot showing sag and tension versus conductor temperature of the conductor for Cycle 1 and 2 are shown in Figures 5 and 6 respectively. Table 2 contains a summary of the results.

The conductor temperature is taken to be the highest reading thermocouple in each conductor. The temperatures of the core and aluminum layers at the start, nominally 240°C and the end of the test are listed in Table 3.

The following general observations are made about the plots.

- The heating cycle produces higher sag than the cooling cycle for the same temperature. That is, there is some hysteresis.
- The test conductor does not exhibit a well-defined kneepoint temperature. The kneepoint is a transition between 80°C to 100°C.
- For the second cycle, after cooling back to room temperature the conductor had less sag by 15mm and higher tension 112 kg than at the start of the test.

Table 2 Summary of High Temperature Test Results

Cycle 1	23°C (Before Heating)	240°C	Net Change
Sag	273mm	1334mm	1061mm
Tension	2083 kg	443 kg	1640 kg
Tension (%RBS)	20.4%	4.3%	15.8%

Cycle 2	23°C (Before Heating)	240°C	Net Change
Sag	280mm (11.0 inches)	1382mm (54.4 inches)	1102mm (43.4inches)
Tension	2050 kg (4519 lb)	427 kg (941 lb)	1623 kg (3578 lb)
Tension (%RBS)	20.1%	4.2%	15.9%

Table 3 Temperatures of Core and Aluminum Layers

Cycle	¼ Point of Span			Centre of Span		
	Core	Middle Al.	Outer Al.	Core	Middle Al.	Outer Al.
1 start	23.0	22.6	22.8	22.0	22.7	22.7
1 240°C	231.6	231.5	232.1	231.3	231.6	240.4
1 end	29.4	29.2	29.2	30.2	31.2	31.4
2 start	23.0	22.7	23.0	21.9	22.6	22.6
2 240°C	222.6	222.6	223.1	231.1	231.2	239.4
2 end	23.0	22.7	22.8	22.1	22.8	22.8

Analysis

Data was analyzed by Dr. Stephen Barrett of Barrett Research to look at how the data compares to predictions from transmission line design software such as Sag10 and STESS (Strain Summation method). Both calculate sag using the Alcoa graphical method. These analyses are shown in Appendix B and were performed independently of Kinectrics Inc. The “compressive stress parameter” or “built-in tensile stress parameter” should be set at –1.45 ksi (-10MPa) for the line design software programs.

CONCLUSION

1. A sag-tension-temperature study on 675TW showed a knee-point transition in the range of 80-100°C.
2. The “compressive stress parameter” or “built-in tensile stress parameter” should be set at –1.45 ksi (-10MPa) for the line design software programs.
3. The line design software programs such as Alcoa Sag10 and STESS predict the sag-tension-temperature behaviour very well.

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ACKNOWLEDGEMENTS AND DISCLAIMER

Kinectrics North America Inc. has prepared this report in accordance with, and subject to, the terms and conditions of the contract between Kinectrics North America Inc. and 3M Company, dated August 15, 2002.

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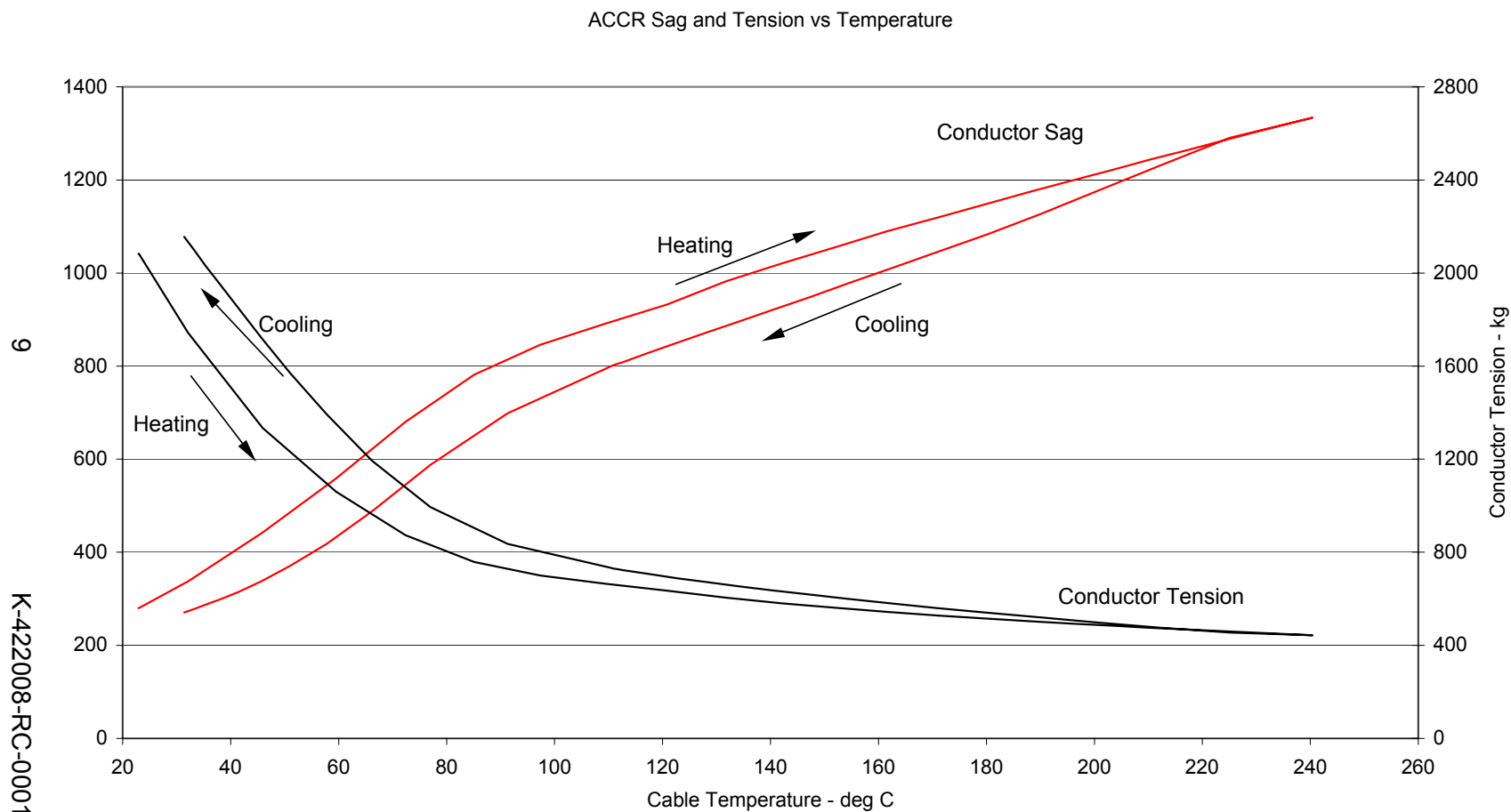


Figure 5 Cycle 1 Conductor Sag and Tension vs. Temperature

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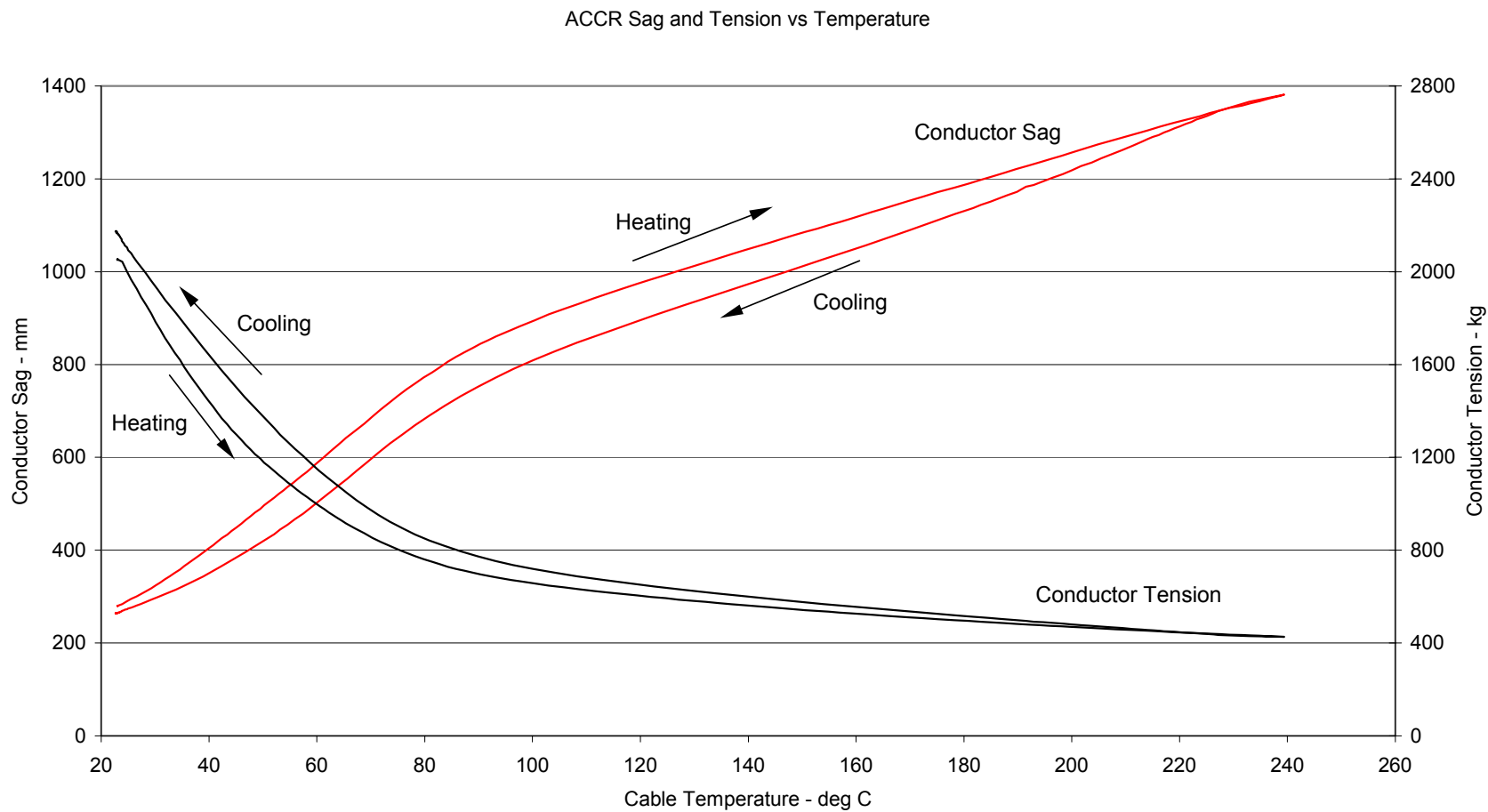


Figure 6 Cycle 2 Conductor Sag and Tension vs. Temperature

APPENDIX A

Specifications for 675 kcmil ACCR Conductors

3M Composite Conductor Specifications - 675/TW

Conductor Physical Properties

Designation		ACCR/675TW
Stranding		20/7
kcmils	kcmil	676
Area Fraction Core	%	10.25%
Weight Fraction Core		12.50%
Diameter		
indiv Core	in	0.105
indiv Al	in	
Core	in	0.315
Total Diameter	in	0.902
Area		
Al	in ²	0.5309
Total Area	in ²	0.5915
Weight	lbs/linear ft	0.726
Breaking Strength		
Core	lbs	11,564
Aluminum	lbs	10,923
Complete Cable	000's lbs	22,487
Modulus		
Core	msi	31.4
Aluminum	msi	7.6
Complete Cable	msi	10.1
Thermal Elongation		
Core	10 ⁻⁶ /C°	6.35
Aluminum	10 ⁻⁶ /C°	23.00
Complete Cable	10 ⁻⁶ /C°	17.69
Heat Capacity		
Core	W-sec/ft-C	13
Aluminum	W-sec/ft-C	275

Conductor Electrical Properties

Resistance		
DC @ 20C	ohms/mile	0.1317
AC @ 25C	ohms/mile	0.1348
AC @ 50C	ohms/mile	0.1481
AC @ 75C	ohms/mile	0.1615
Geometric Mean Radius	ft	0.0355
Reactance (1 ft Spacing, 60hz)		
Inductive Xa	ohms/mile	0.4052
Capacitive X'a	ohms/mile	0.0973

APPENDIX B

Report on 675 kcmil (20/7) ACCR/TW Heat-Run Tests at Kinectrics

November 24, 2003

Prepared by:

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- 1) Introduction
- 2) Change of “Inner Span” with Tension.
- 3) Measured and Calculated Sags of ACCR
- 4) Measured and Calculated Sags of ACSR
- 5) Discussion of Compressive Stress.
- 6) Sag Comparison for a 1000 ft Span

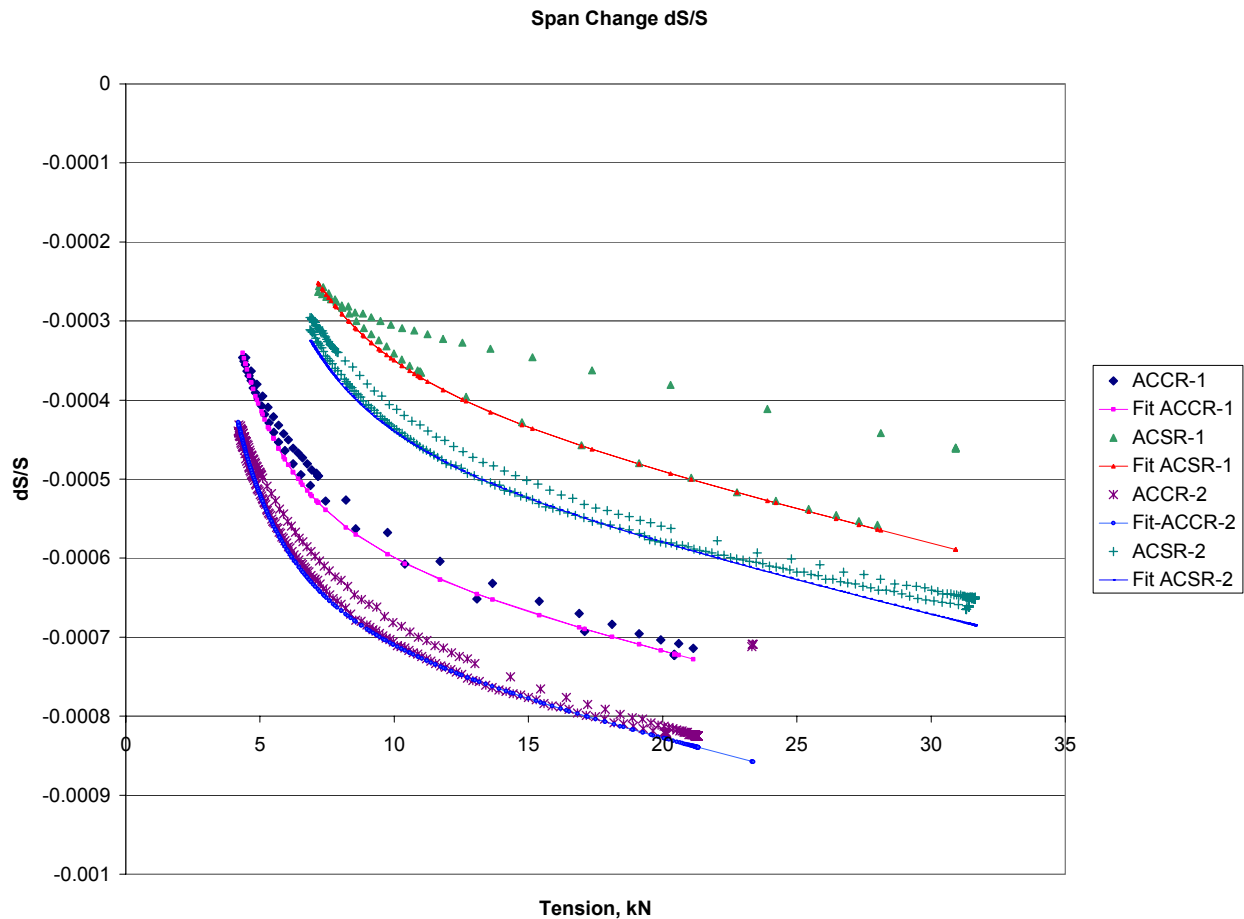
1) Introduction

The two heat cycles on 675 kcmil (20/7) ACCR/TW were performed by Kinectrics on October 9 & 10, 2003. The “Total Span” was approximately 225 ft. and the “Inner Span” (excluding end hardware) was 215 ft. The Hardware at the South end was 5.17 ft. long and weighed 16.4 lb. The hardware at the North end was 5.17 ft long and weighed 9.6 lb. Heat runs were performed simultaneously on a parallel sample of 795 kcmil (26/7) ACSR.

Each inner-Span Sag was measured by 3 String Potentiometers (“String-Pots”), one at centre-span and one at each end of the inner span. Tension was measured by a load cell at the north end.

2) Change of Inner Span with Tension

Horizontal string-pots were used to record the change of the inner span, which changed for two reasons: elastic movement of the supports and the effect of the length and weight of the terminal hardware.



Each curve can be decomposed into elastic support movement and the effect of terminal length and weight. The span gets longer as the temperature rises and the tension drops, as expected.

However, there is some hysteresis in the horizontal string-pot readings and also in the sags. When the temperature drops and the tension increases, the span does not shorten all the way back to its original position. This hysteresis in span length results in a sag hysteresis, so that the sags during the decreasing-temperature portion of the heat-cycle are reduced.

During the first heat cycle, the ACSR curves for rising and falling temperature are quite different, suggesting that the rising and falling curves for sag should also be different. This is not the case, however, indicating that something went wrong with the ACSR's horizontal string-pots during part of the first cycle. This problem did not occur during the second cycle. The data suggest that the end supports are not twisting very much. (Both spans elongate elastically at approximately the same rate as a function of the tension of each conductor individually). It is not clear whether the support movements for the two conductors are independent or whether the two conductors cooperate in moving the supports. From the point of view of data analysis, it doesn't really matter.

The span-elongation curves were fitted by:

$$\delta S/S = C - \text{ELAST} \times H + \text{TERM} / H^2 \text{ for tension } H \text{ in kN.}$$

	ELAST	TERM
ACCR	8×10^{-6}	.005
ACSR	8×10^{-6}	.008

The constant term defines a reference span length and may be discarded after fitting. Discarding this term defines the reference inner span length as the length of the span without conductor (zero tension on the supports) and with the terminal hardware held in a horizontal orientation.

The linear term is elastic movement of the supports. The $1/H^2$ term accounts for the effect of the length and weight of the terminal hardware. This fit is entered into the sag-tension program in order to take the changing span length into account when calculating sags and tensions.

The theoretical value of "TERM" is given by:

$$\text{TERM} = (1/8S)[L_L(wS + M_L)^2 + L_R(wS + M_R)^2]$$

where $S = 215$ ft

$w = 0.726$ lb/ft

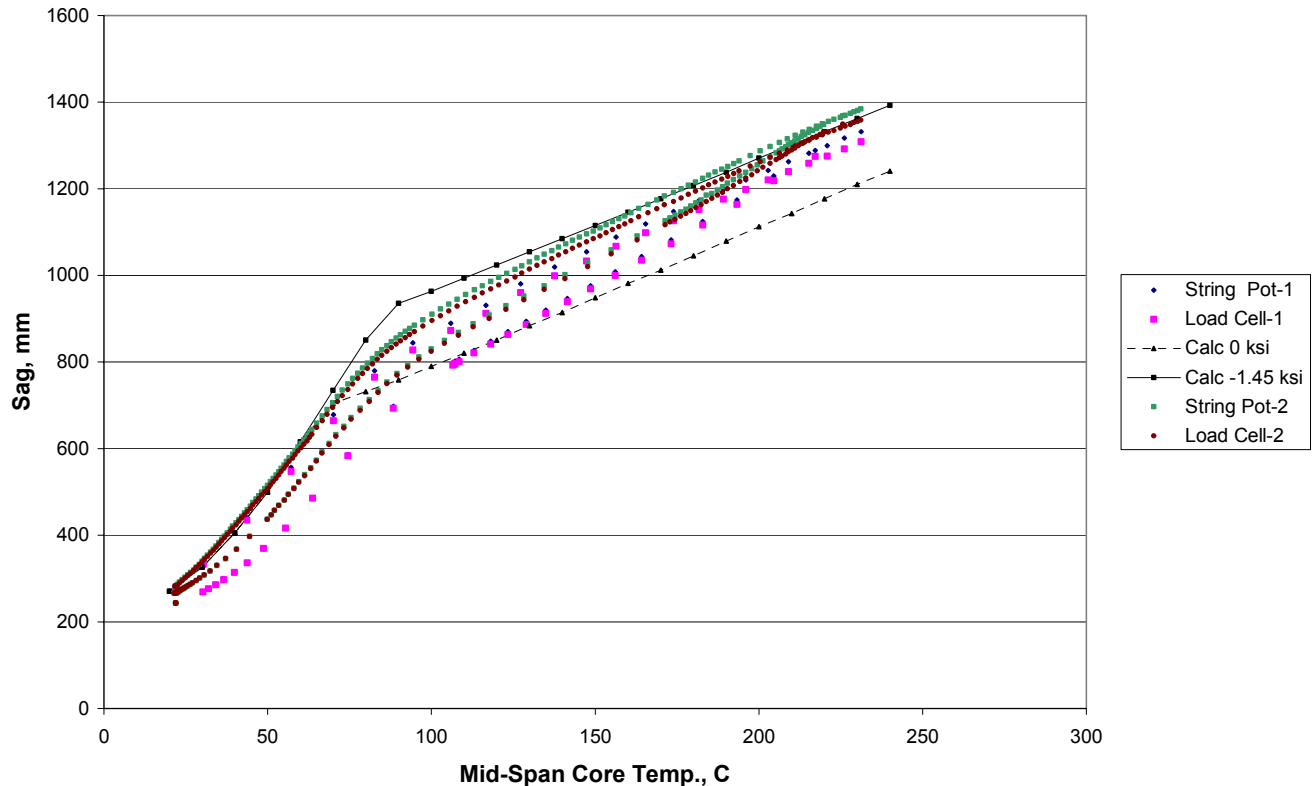
The terminal lengths are each 5.17 ft

The terminal weights are 16.4 lb (south) and 9.6 lb (north)

These values lead to a theoretical value of $\text{TERM} = 172 \text{ lb}^2 = 0.0034 \text{ kN}^2$ for the ACCR. The measured value was 0.005, which is somewhat higher. This may be because it is difficult to completely eliminate the weight of the current connections and leads during the test. This weight was not taken into account in the theoretical calculation. The measured value was used to correct the sag-tension calculations.

3) Measured and Calculated Sags of ACCR

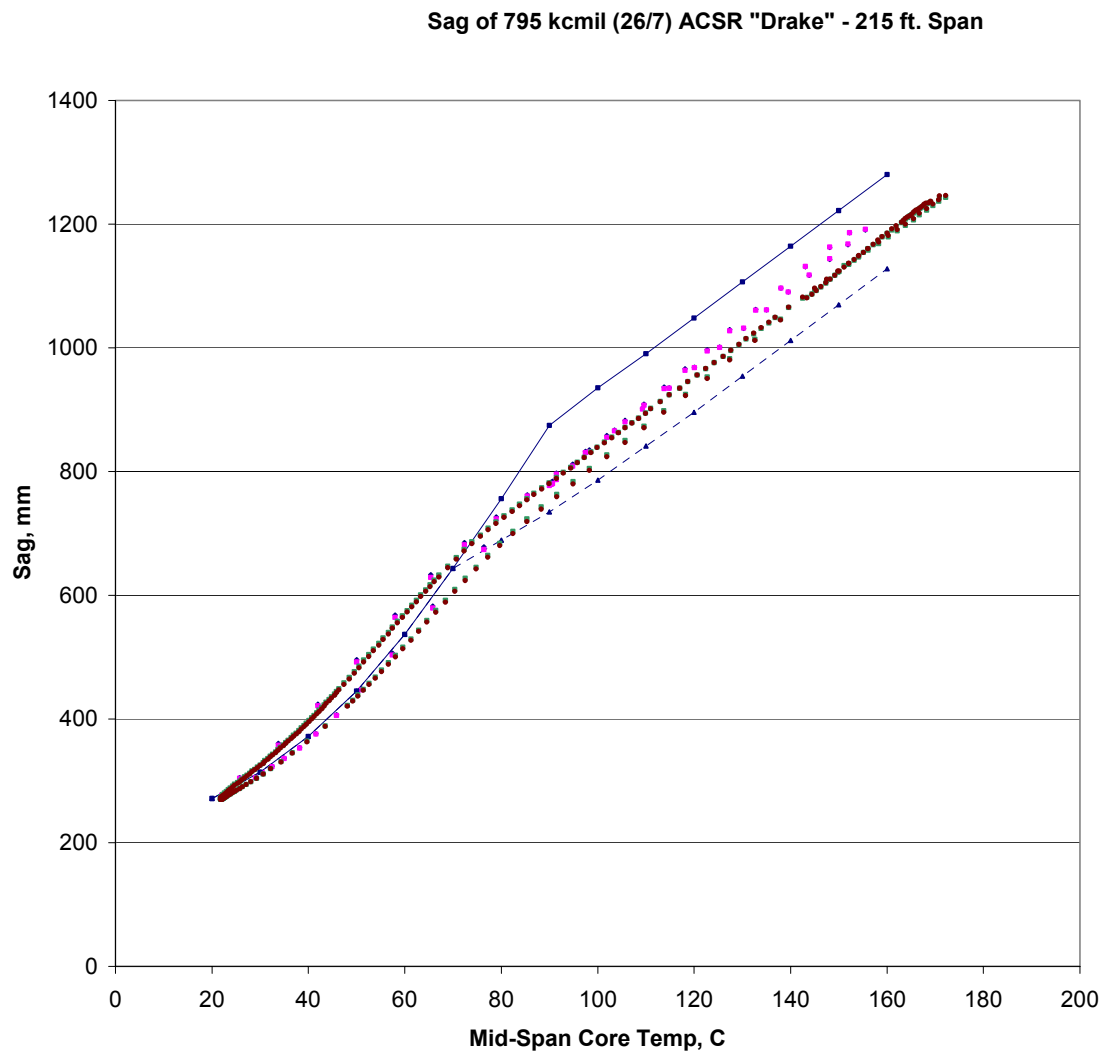
Sag of ACCR/TW675 (TWD605-T11) - 215 ft. Span



The sags as measured by string-pots are in very close agreement with those computed from the load-cell tensions. Sags were also calculated by the Strain-Summation Method for zero compressive aluminum stress and for -1.45 ksi above the knee-point temperature. The knee-point is not very distinct in this case and is smeared between 70°C and 90°C . The high-temperature sags fall between the 0 ksi and -1.45 ksi curves, except for some string-pot measurements during the second heat cycle, which slightly exceed the -1.45 ksi curve. (The corresponding Load-Cell sags coincide with the -1.45 ksi curve. **The continued use of -1.45 ksi (-10 MPa) compressive aluminum stress is recommended.** The hysteresis that was seen in the change of span length in the first graph, shows up as reduced sags during the decreasing-temperature portion of the heat cycle. A small proportion of this hysteresis may also be caused by hysteresis in the stress-strain curves, which is not normally considered in sag-tension programs.

The small increase of sag (~ 50 mm) in cycle 2 compared with cycle 1 is likely due to a slight twisting of the supports because there is the same amount of discrepancy in the ACCSR data below, but in the opposite direction. The data have not been corrected for support movement but the fits have been corrected in an attempt to match the observed sags. The support movement was fitted to cycle 1 and the same parameters were used for cycle 2. Perhaps a more careful fitting of the support movement in cycle 2 would correct these small discrepancies.

4) Measured and Calculated Sags of ACSR



5) Discussion of Compressive Stress

Over the past few decades, it has become normal practice (STESS) to use a default value of compressive aluminum stress (-10 MPa or -1.45 ksi) at high temperatures. As can be seen in the ACCR graph, above, this would add approximately 165 mm (6.5 inches) to the calculated sag. This precaution would overestimate the calculated sag at 240°C by approximately 1.3 inches.

An alternative to using a default value of compressive stress is described in:

Some Effects of Mill Practice on the Stress-Strain Behavior of ACSR,
C.B. Rawlins,
IEEE Trans on Power Delivery, Vol. 14 No. 2, April 1999, pp 602-629.

This method is used in program SAG10 and assumes that the conductor manufacturing process produces a residual or “built-in” tensile stress of approximately +10 MPa (+1.45 ksi) in the conductor. The “built-in tensile stress” model of SAG10 augments the calculated high-temperature sags by the same amount as the compressive stress model of STESS.

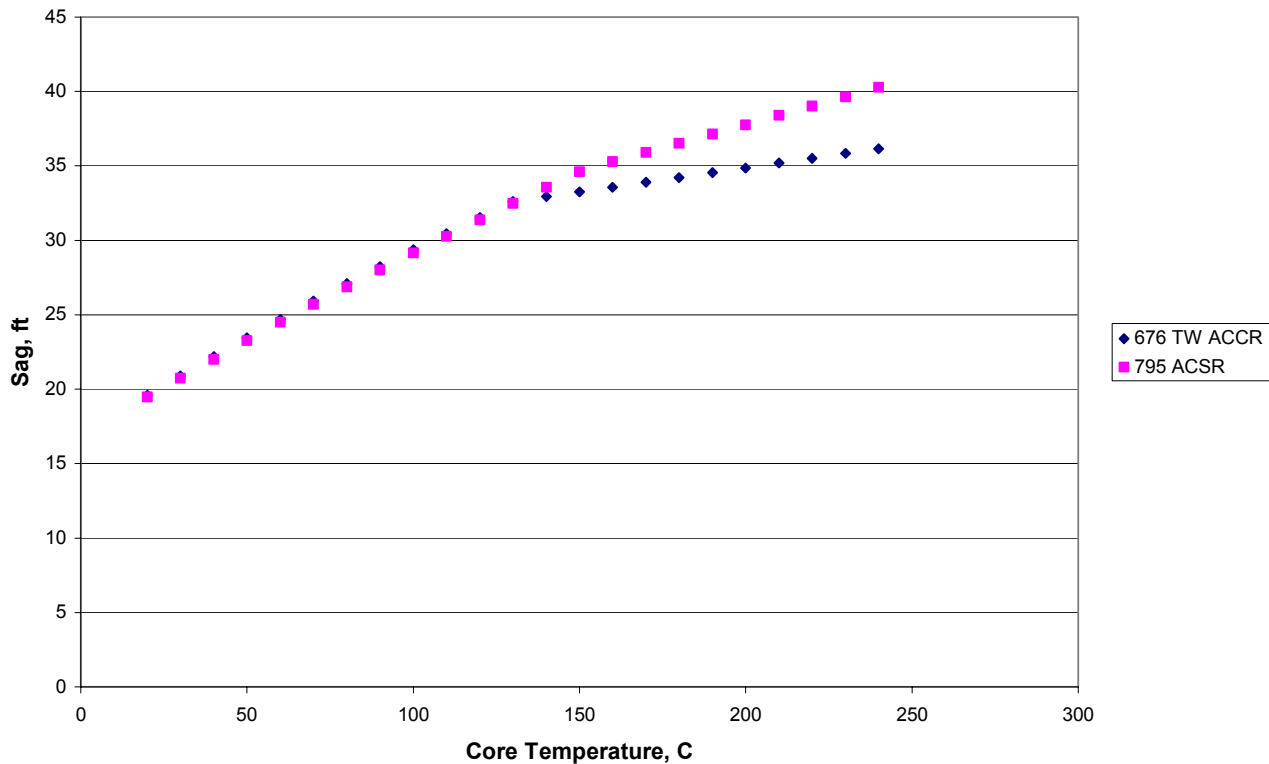
In the data plotted above, neither the large compressive stresses of the STESS model nor the large “built-in” tensile stresses of Rawlins’ model occur at the knee-point. Instead there appears to be a gradual build-up of compressive stress beginning above the knee-point. This is in agreement with both Rawlins’ model (without the “built-in” stress) and Barrett’s detailed model mentioned in his Discussion in Rawlins’ paper.

In view of the possibility of larger compressive stresses, depending on conductor manufacture (especially the effect of lay angles), **it is recommended to continue using the default value of compressive stress for estimating high-temperature sags.** In the present test, the sag at 240°C is overestimated by approximately 1.3 inches.

6) Sag Comparison for a 1000 ft Span

The following graph compares the sags of 675TW ACCR with those of 795 ACSR at the same temperatures. These calculated sags are based on a limiting compressive stress of -1.45 ksi in the aluminum at high temperature. The starting sags are matched @ 22°C as they were in the laboratory test, using 2083 kg (4592 lb) for the ACCR and 3152.6 kg (6950 lb). The aluminum stress at 20°C was computed to be 5.7 ksi for the ACCR and 5.6 ksi for the aluminum, which is an indication that they should have similar self-damping characteristics.

Sags of 675 TW ACCR and 795 ACSR - 1000 ft Span (-1.45 ksi compression)



The low-temperature sags of the two conductors are essentially the same. Even though, the core of ACCR has a lower expansion coefficient, it is a smaller proportion of the total conductor area. (The ACCR is Type 11 and the ACSR is Type 16).

The sag comparison here is not really fair to the ACCR because:

1. The comparison ought to be with ACSR having the same proportion of core area.
2. The comparison ought to be based on similar sized conductors operating at the same current, not the same temperature. ACCR has an advantage because of its higher core conductivity.
3. It should also be noted that ACSR cannot actually be operated up to 240°C without damaging the galvanizing on its steel core.
4. It also may not be fair to compare the conductors with the same starting sag, since ACCR has a higher strength-to-weight ratio. It may be possible to string ACCR with less sag than ACSR, but vibration protection and heavy loading conditions need to be considered to determine proper stringing sags.

DISTRIBUTION

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