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KINECTRICS NORTH AMERICA INC. TEST REPORT FOR 3M COMPANY TO DETERMINE THE SAG – TEMPERATURE – TENSION PERFORMANCE OF 774 KCMIL 3M™ COMPOSITE CONDUCTOR

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INTRODUCTION

A Sag – Temperature – Tension Test was performed for 3M Company on their 3M™ 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 owns all data and copyright to this information.

A sag-tension-temperature study on 774 kcmil ACCR showed a knee-point transition in the region of 60°C. The "compressive stress parameter" or "built-in tensile stress parameter" should be set at -1.45 ksi (-10 MPa) for the line design software programs. The line design software programs such as Alcoa Sag10™ software and STESS predict the sag-tension-temperature behaviour very well.

TEST OBJECTIVE

The objective of the Sag – Temperature – Tension Test was to determine the sag and tension of the 774 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.

Additional information on the current-temperature relationship for the conductor was obtained by selecting several arbitrary current levels and measuring the resulting temperature. These measurements were performed at known conditions so the results could be compared to ampacity calculations based on IEEE Std 738. The known conditions would be no wind, no sun, ambient temperature and altitude. The conductor was essentially in "new" condition so the emissivity and absorptivity could be estimated to produce a best fit to the calculations.

TEST CONDUCTOR

The conductor tested was designated ACCR-774-T53, 46/37 manufactured by 3M Company. The construction of this conductor has 46 heat-resistant aluminum-zirconium alloy wires in 2 layers surrounding 37 core wires in 3 layers. The outside diameter of the conductor is 1.254 inches (28.1mm). The rated tensile strength (RTS) of the conductor is 71,010 lbf (32,210 kgf). This particular conductor construction has a high core fraction (33% core by area), and is an example of a construction intended for use in long span crossings.
The data sheet on the 774 kcmil ACCR conductor used in the sag – temperature – tension test is contained in Appendix A.

Approximately thirty-nine (39) 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.

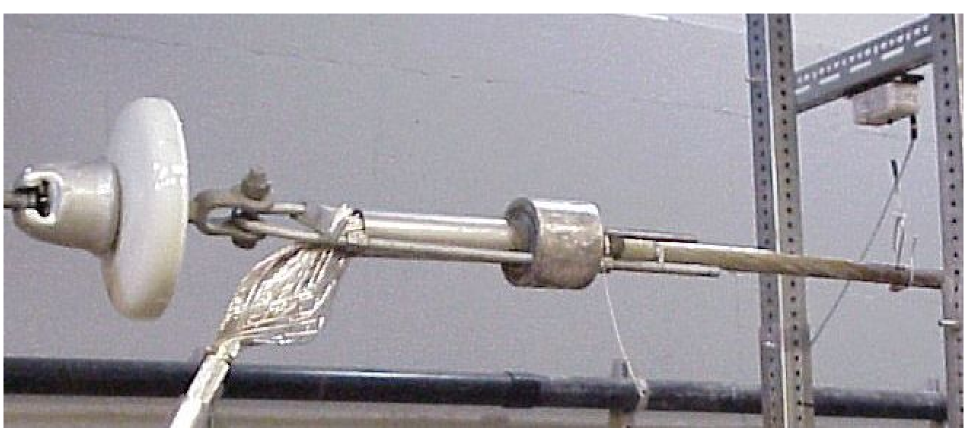
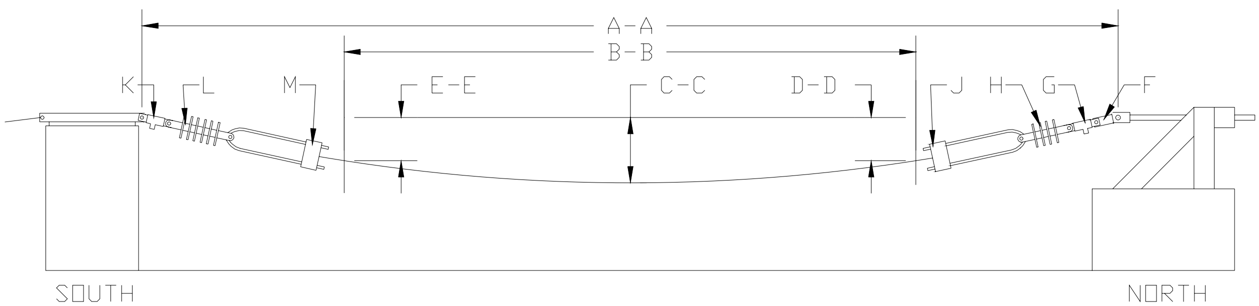


Figure 1 Epoxy Dead-end

TEST SET-UP

Test Apparatus

The Sag – Temperature – Tension Test was carried out at Kinectrics' Conductor Dynamics Laboratory. The laboratory is temperature controlled to 22ºC ±2ºC with minimal air movement. A schematic of the setup is shown in Figure 2. The maximum span length (i.e. tension eye to tension eye) was 39.9 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.



A-A	Overall span length (68.8 m)	G	North Load Cell
B-B	Span length between North and South Sag Measurement	H	North Insulator (4 skirt)
C-C	Sag at mid-span	J	North epoxy dead-end assembly
D-D	Sag at North end just inboard of hardware	K	South Load Cell
E-E	Sag at South end just inboard of hardware	L	South Insulator (6 skirt)
F	Strain Plate	M	South epoxy dead-end assembly

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 two large ACSR conductors, (return conductor) to complete the circuit back to the current transformer. The return conductors were untensioned and were positioned on insulating pads on the floor.

Instrumentation

<u>Conductor Tension</u>

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.

<u>Conductor Temperature</u>

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 (¼ 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 – In the core
Thermocouple #2 – Between the core and aluminum-alloy wire in the middle layer
Thermocouple #3 – Between two aluminum-alloy wires in the middle layer
Thermocouple #4 – 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.

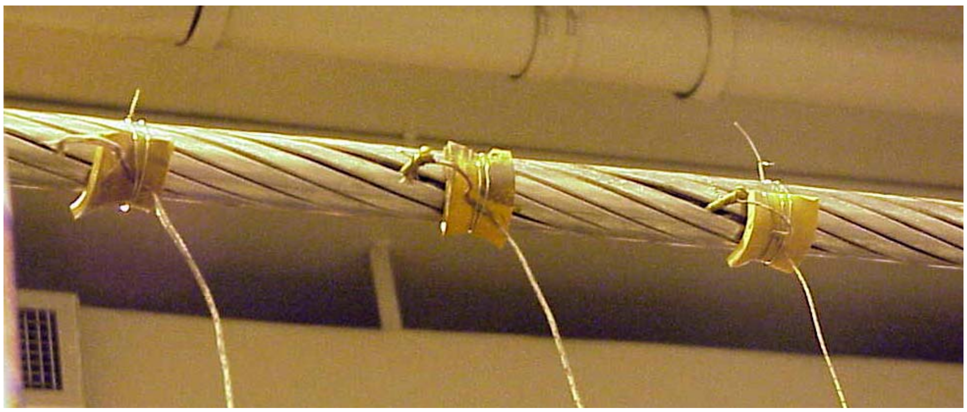


Figure 3 Typical Thermocouple Installation (example is from a different conductor construction)

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 inboard of the end fitting attachment points. 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 was cooled. Two (2) potentiometers were located at each end of the span. This setup is shown in Figure 4.

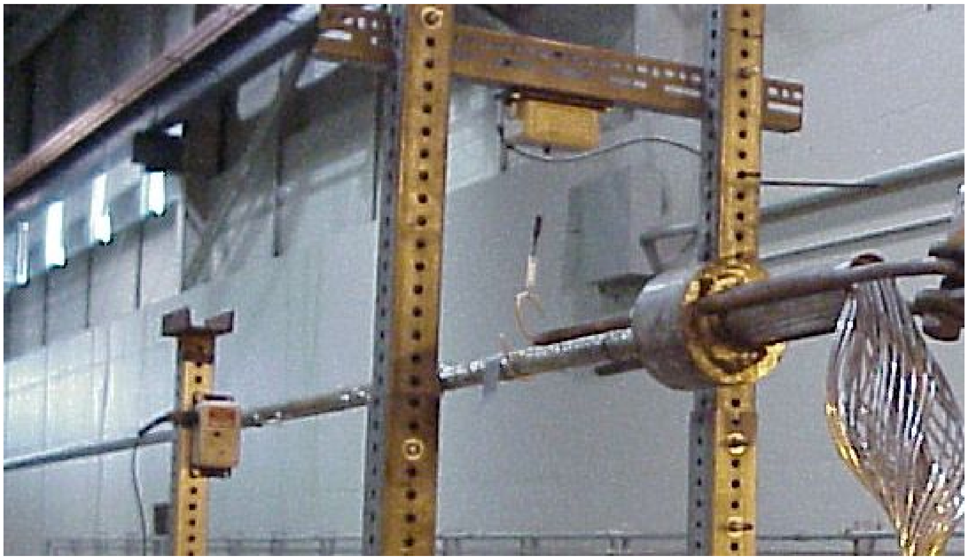


Figure 4 Test Setup Near Dead-end

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 6 seconds when the change in sag-temperature was greater, and reduced to every 30 seconds when the conductors were at steady-state temperature.

To achieve the target conductor temperature of 240ºC the circulating current was established by connecting the conductor to the appropriate taps on the current transformer. The actual current and resulting temperature was determined by the loop impedance of the electrical circuit.

TEST PROCEDURE

The 774 kcmil conductor was initially tensioned to 14,250 lbf (6,464 kgf) or 20% RTS at room temperature. The pull-wire potentiometers were "zeroed" at this condition.

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 the target temperature as soon as the highest reading thermocouple measured at least 240°C. The cuurent was left on for sufficient time to let the conductor attain a thermal equlibrium. The current was then turned "OFF" and the conductors were allowed to cool by natural convection to room temperature. . The details of the cycle is listed in Table 1.

Table 1 Summary of Test Parameters

Parameter	Value
Max Temp. of 774 kcmil ACCR	250ºC
Temperature rise above ambient (23ºC)	227ºC
Temp. rise time 23ºC to 240ºC	68 minutes
Average heating rate	3.3ºC/min
Cooling time 240º to ambient (23ºC)	3 hours 11 minutes
Average cooling rate 240ºC to ambient (23ºC)	0.8º/min

Current-Temperature Relationship Measurements

To measure the current-temperature relationship, the current circulating in the conductor was adjusted by changing the tap positions on the current transformers. Once the current was established, the temperature in the conductor was given sufficient time to stabilize. Once this steady-state condition was attained then the system was in thermal equilibrium and the current and corresponding conductor temperature could be made.

TEST RESULTS

A plot showing sag and tension versus conductor temperature of the conductor is shown in Figure 5. 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 before heating, at the steady state condition, and after cooling for each cycle 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 in a region around 60ºC.
- The sag curve looks unusual because it curves upwards rather than leveling off as expected. This is an artifact of the short-span relative to the conductor size. In actual fact the behavior is well predicted and this is explained in Appendix B.

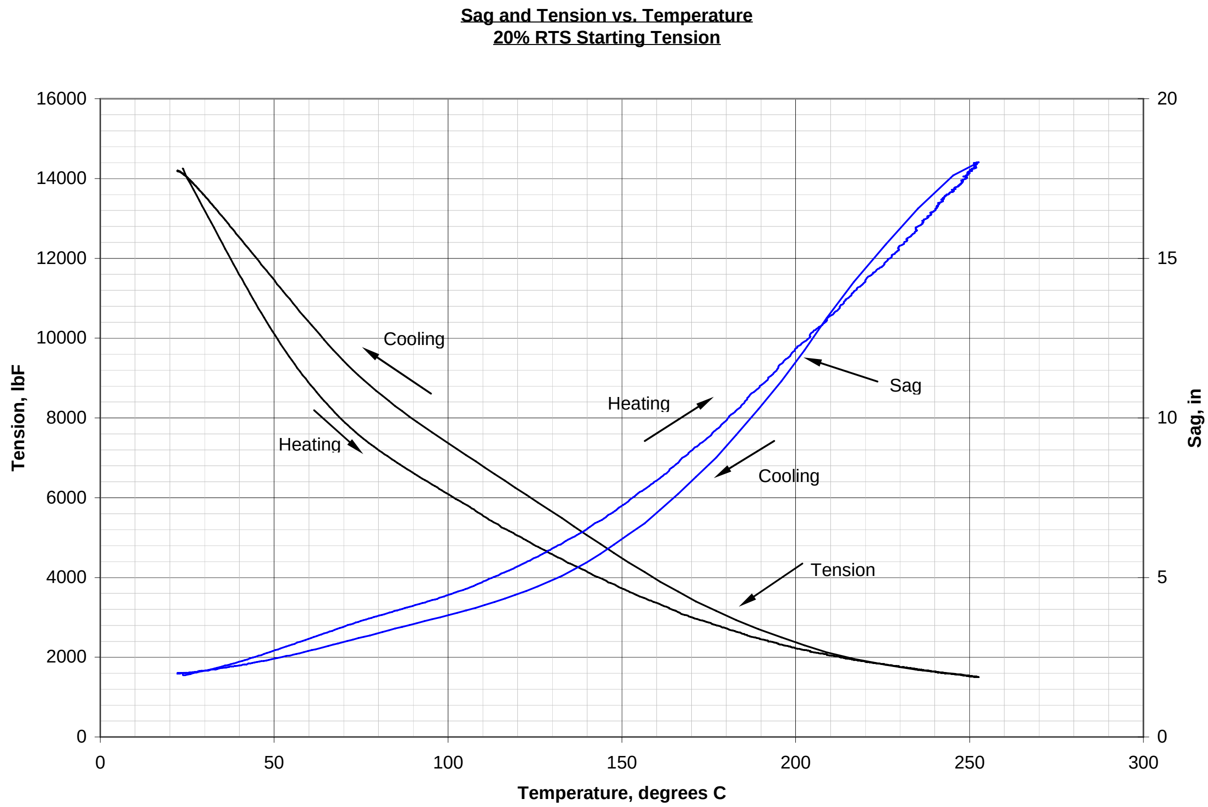


Figure 5 Conductor Sag and Tension vs. Temperature

Table 2 Summary of High Temperature Test Results

	23ºC (Before Heating)	250ºC	Net Change
Sag	1.9 inch (48mm)	18.0 inch (457 mm)	16.1 inch (409 mm)
Tension	14251 lbf (6464 kg)	1506 lbf (583 kg)	12745 lbf (5781 kg)
Tension (%RBS)	20%	2.1%	17.9%

Table 3 Temperatures of Core and Aluminum Layers

	Core	Between Core-Inner Layer	Between Two Inner layer strands	Between two Outer layer strands
Before heating	23	23	23	23
At steady state	250	252	251	245
After cooling	23	22	23	23

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^{TM} software 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 (-10 MPa) for the line design software programs.

Current-Temperature Relationship Measurements

Seven (7) different currents were circulated through the conductor. They were 1630 A , 1502 A, 1290 A, 1070 A, 700 A, 564 A, and 420 A.

The corresponding steady-state conductor temperatures, including the condition at 250C, are shown in the following table.

Steady-State Current	Steady-State Conductor Temperature
1630	252
1502	210
1290	165
1070	122
700	66
564	49
420	36

A plot showing the steady-state currents versus conductor temperatures are shown in Figure 7. The temperature plotted is the hottest of the measured thermocouples. An exponential curve is fitted through the points.

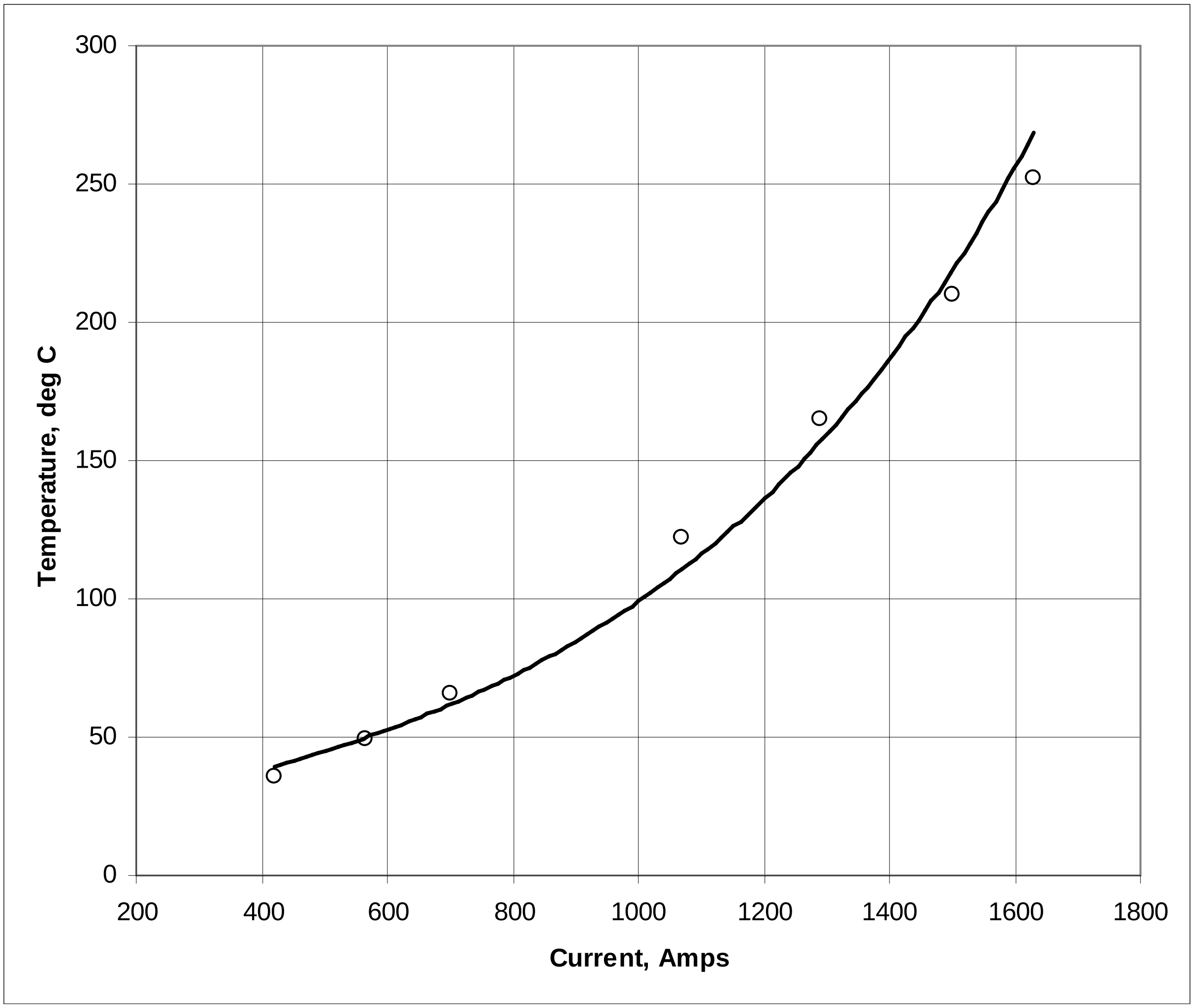


Figure 7 Conductor Temperature vs. Circulating Current

The predicted ampacity was supplied by 3M Company using RateKit™ software and selecting the IEEE 738 Transient Ampacity Method. The comparison with the measured data is shown in Figure 8. Since the experiment was performed indoors, the parameters selected for the model inputs included no solar effects, zero wind speed, and an ambient temperature of 25°C for <1200 amps and 35°C for > 1200 amps. There is reasonable agreement between the data and the model prediction.

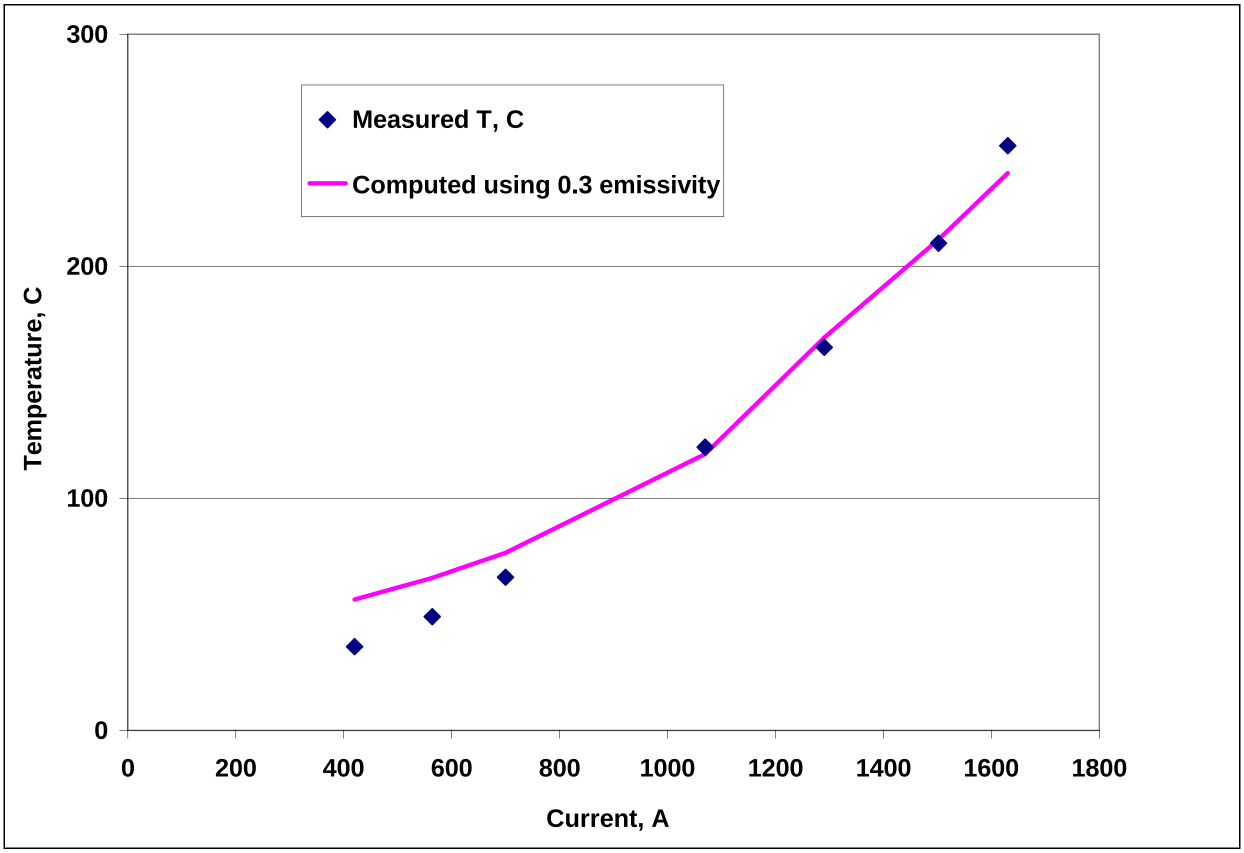


Figure 8 Predicted and Measured Conductor Temperature vs. Circulating Current

CONCLUSIONS

1. A sag-tension-temperature study on 774 kcmil ACCR showed a knee-point transition in the range of 60°C.
2. The “compressive stress parameter” or “built-in tensile stress parameter” should be set at –1.45 ksi (-10 MPa) for the line design software programs.
3. The line design software programs such as Alcoa Sag10™ software and STESS predict the sag-tension-temperature behaviour very well.

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ACNOWLEDGEMENTS 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 9, 2004.

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APPENDIX A

Specifications for 774 kcmil ACCR Conductor

Conductor Physical Properties

Designation		ACCR_774-T53
Stranding		46/37
kcmils	kcmil	774
Area Fraction Core	%	34.52%
Weight Core	lb/ft	0.48
Diameter		
indiv Core	in	0.105
indiv Al	in	0.130
Core	in	0.735
Total Diameter	in	1.254
Area		
Al	in^2	0.6077
Total Area	in^2	0.9280
Weight	lbs/linear ft	1.202
Breaking Strength		
Core	lbs	57,885
Aluminum	lbs	13,125
Complete Cable	lbs	71,010
Modulus		
Core	msi	32.9
Aluminum	msi	8.8
Complete Cable	msi	17.1
Thermal Elongation		
Core	$10^{-6}/C^{o}$	6.35
Aluminum	$10^{-6}/C^{o}$	23.00
Complete Cable	$10^{-6}/C^{o}$	11.96
Heat Capacity		
Core	W-sec/ft-C	84
Aluminum	W-sec/ft-C	272

Conductor Electrical Properties

Resistance		
DC @ 20C	ohms/mile	0.0970
AC @ 25C	ohms/mile	0.0993
AC @ 50C	ohms/mile	0.1091
AC @ 75C	ohms/mile	0.1190
Geometric Mean Radius	ft	0.0366
Reactance (1 ft Spacing, 60hz)		
Inductive Xa	ohms/mile	0.4013
Capacitive X'a	ohms/mile	0.0876

APPENDIX B

Report on
774 kcmil T53 (46/37) ACCR
Heat-Run Tests at Kinectrics

October 1, 2005

Prepared by:
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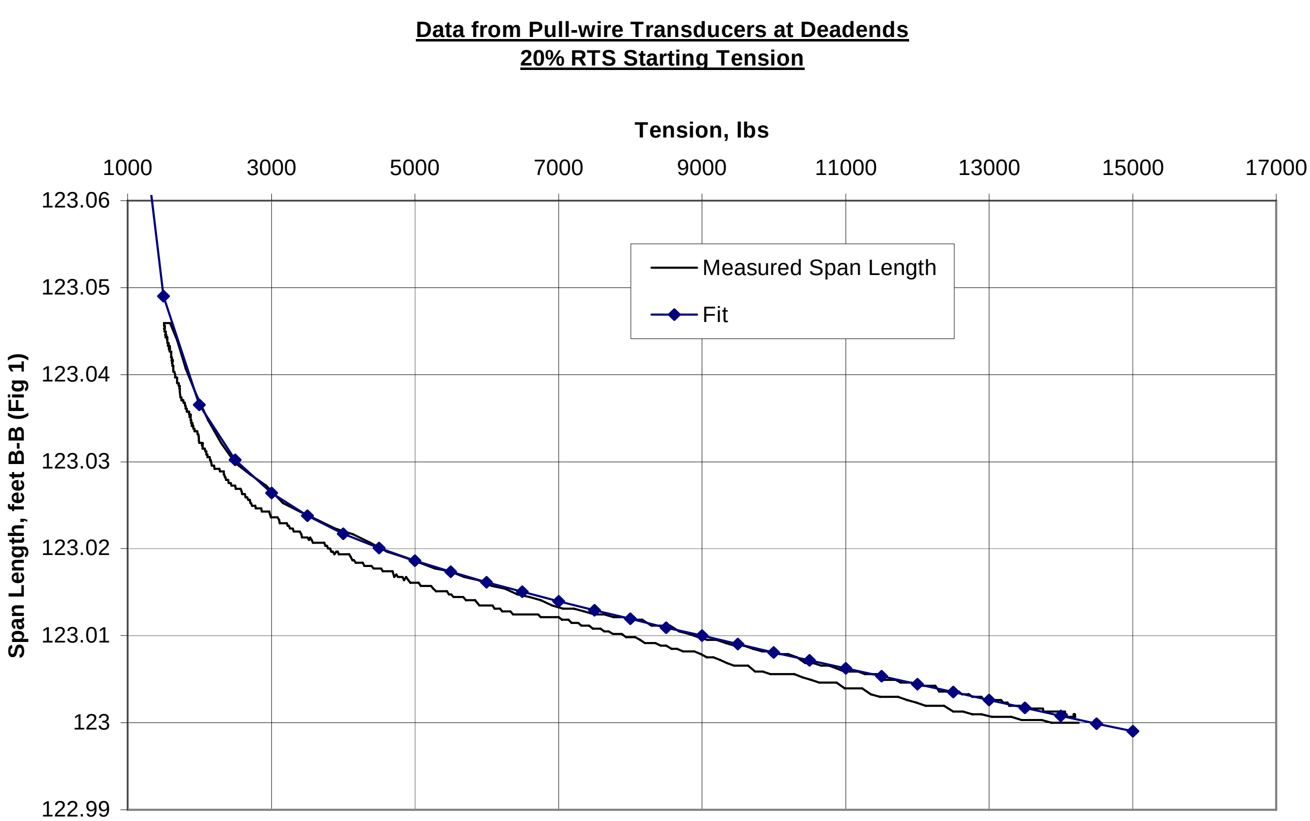
774 kcmil T53 (46/37) ACCR
Tested by Kinectrics on September 14, 2005
Analysis by Barrett Research, October 1, 2005

Introduction

Kinectrics tested a 123 ft. span of 774 kcmil T53 (46/37) ACCR (Rated Tensile Strength = 71,010 lbf), which has a large core for river-crossing purposes. The tension was 14,251 lb (20% RTS) @ 23.7°C at the start of the test at 14:13 on September 14, 2005.

Because the span is so short, the weight and length of the dead-ends and any small "pole deflection". has a large effect on sags and tensions. For this reason, Kinectrics used string transducers to measure the varying span length throughout the test. The vertical displacements were also measured at mid-span and at the mouths of the two dead-ends, so that the sag contribution from drooping dead-ends could be removed from the test. The measured sag was equal to the mid-span height minus the average of the heights at the mouths of the dead-ends. This sag was found to be in good agreement with sag computed from the tension.

A fit to the rising-temperature curve has been added to Kinectric's graph of span length:

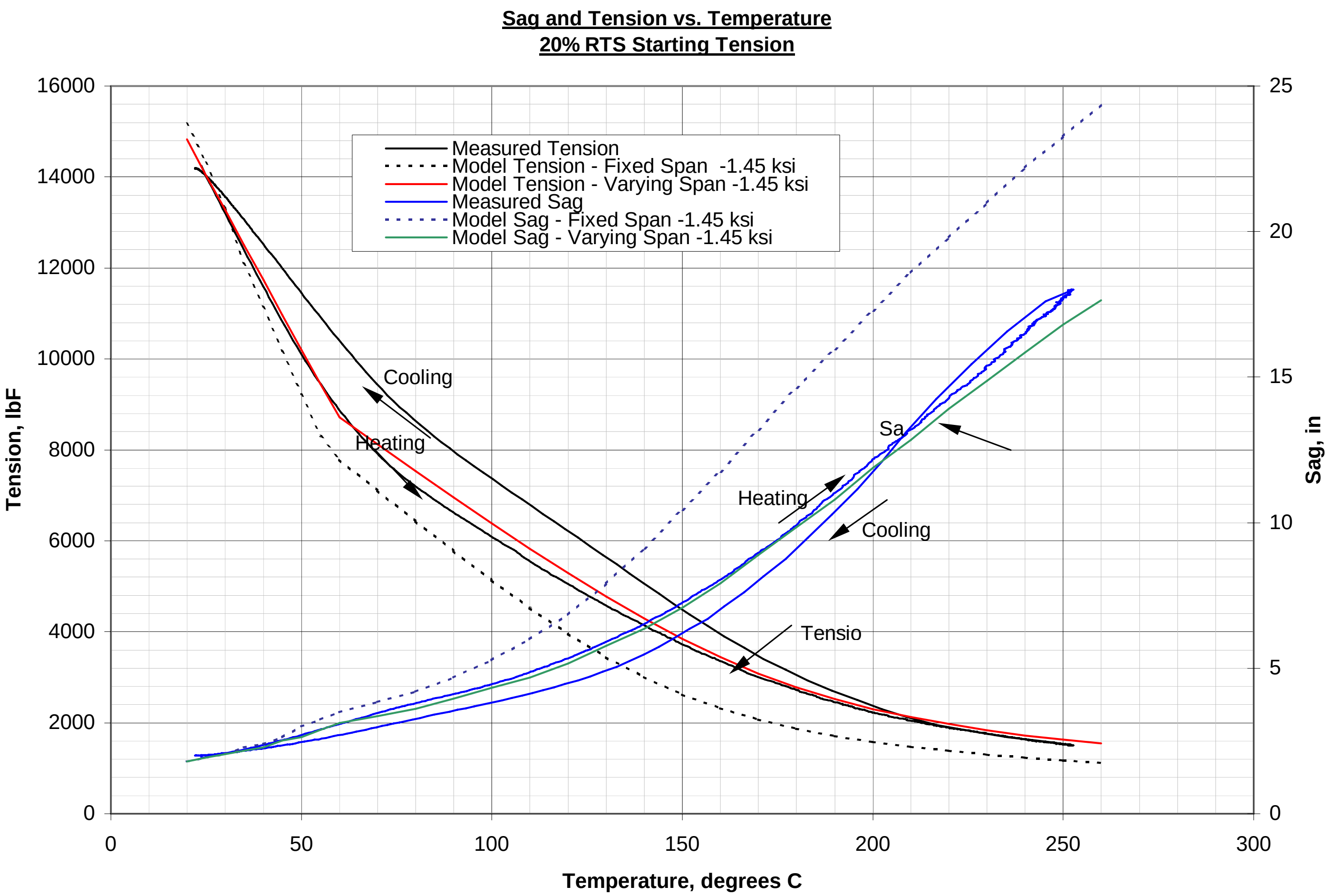


The fit is described by:

$$Span = 123.025 + \frac{60{,}000}{H^2} - 1.75 \times 10^{-6} H$$

where span is in feet and tension ***H*** is in lbf. The first term is caused by the droop of the dead-ends at high temperatures (low tensions) and the second term is a small but significant elastic deflection in the end hardware.

The following graph is Kinectrics' graph of tension and sag vs temperature. Temperature is the maximum of six thermocouples, which turns out to be the core temperature. The model calculations were performed for both a fixed span (dashed lines) and a span varying according to the equation above. The default compressive load of –1.45 ksi (-19 MPa) was used. Stress-strain and creep properties of the core and aluminum were taken to be the same as 3M's 1272 kcmil ACCR. Sag tension calculations were performed using STR4 (Version 4 of the Strain-Summation Method, a descendant of STESS).



Results

The model calculations are in good agreement with the measured values of tensions and sags for rising temperature. (The variation of span was fitted to the rising-temperature span-length curve in the previous graph.)

The sag curves look unusual because they curve upwards rather than levelling off as expected. The reason is that the span length is very short, which produces a flat catenary, which, in turn, leads to a concave-upwards shape of the sag-temperature curve. For longer spans, this concavity is limited to the lower portion of the curve. The concavity is caused by elastic contraction of the conductor as the tension drops. This contraction counteracts part of the thermal elongation. The counteracting effect is greater at low temperatures where the rate of change of tension is highest. The concave upward shape can mask the knee-point which can be seen in the model curves at approximately 60°C. The knee-point is not very visible in the measured curves because variability of tension in the aluminum wires tends to smooth out the knee-point.

Conclusions

The behaviour of the conductor is very close to what the model predicts. The model has not been “fitted” to the measured curve. Its predictions are based only on the usual material properties of the ACCR materials, using the default value of compressive aluminum stress. The effect of the latter is small in any case because of the large core. The only other inputs were the starting temperature and tension and the measured variability of span length. For long spans, the appearance of the sag-temperature graph will have a more normal appearance and corrections for variation of span length are not normally required. The test was very well executed and there is no need to repeat it.

DISTRIBUTION

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