# TEMPERATURE VARIATION OF OVERHEAD ELECTRICAL CONDUCTORS AS FUNCTION OF ALUMINUM WIRE RUPTURE

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***Abstract.*** *The Brazilian transmission system is characterized by installations that average 20 years of operation. Competitiveness of the energy sector, lack of resources for new investments and the aging of the system lead to the necessity of not only to reform but also to optimize it in order to face the increasing demand of the Brazilian energy market. The overhead electrical conductor is naturally the most important element on the transport of electrical energy and requires careful predictive and preventive maintenance programs. Therefore, it is of fundamental importance to predict the operational life of overhead electrical conductors using mathematical models so that their energy transport capacity can be optimized. However, it is necessary that such models be validated by test programs so that their estimates can be trusted. One of the most important factors on the structural decay of overhead electrical conductors is the variation of the temperature profile in the event of the rupture of one or more of its Aluminum wires by fatigue or fretting. Thus, temperature profile models must be validated through test programs that experimentally establish mathematical relationships considering effects such as contact resistance, material thermo-mechanical properties modifications, material annealing and presence of defects. The objective of this work is to evaluate the effect of increasing Aluminum wire rupture on the temperature profile of a Penguin overhead electrical conductor, not only on the section of the damage but also along the length of the conductor. A test procedure was developed to evaluate this effect and a test program was conducted. Results showed that the temperature profile dependency of increasing wire rupture is not linear and includes effects other than the cross section loss.*

***Keywords:*** *overhead conductor, temperature profile, wire rupture*

## 1. INTRODUCTION

The conductor is the most important component in the electrical energy transmission requiring careful predictive and preventive maintenance, in order to avoid interruptions of electrical energy supply to several segments of customers. In the event of interruption occurrence, the provider company would be subject to penalty due to the unavailability of the installation (Aluminum Association, 1989).

The predictive maintenance of conductors must be considered as an important tool in the development of techniques that are able to guarantee the reliability of transmission lines, and the study of the thermal behavior of the conductor in the occurrence of Aluminum wire rupture is important in this context (Deb, 2000). In order to introduce a model of temperature variation with respect to the wire rupture in conductors, it is necessary to perform tests that could establish experimentally mathematical relations for specific conductors. The increase of the electrical resistance of the conductor with wire rupture and, consequently, the increase of the temperature by Joule´s effect can be initially modeled using a linear reduction of the transmission area when an increasing number of wires cut, since the electrical resistance of the wire is a function of its cross section. However, local effects such as the contact resistance, the material annealing, the existence of defects, etc., can change these relations (Harvey, 1972; Morgan, 1979).

Therefore, the objective of this work is to develop a test procedure to experimentally evaluate the effect of wire rupture in the temperature profile of a conductor. Test results and theoretical predictions (Morgan, 1991) are compared and discussed.

## 2. EXPERIMENTAL PROCEDURE

The Penguin overhead conductor ACSR 4/0 – 6/1 wires (Aluminum Association, 1989; NBR-7270, 1978) was selected due to its geometric simplicity. Its cross section, schematically presented in Fig. 1, is composed of six Aluminum alloy wires surrounding a steel core wire. The test specimen of the conductor is designed according to Fig. 2. The thermocouple distribution in circumferential and axial directions is also showed in both Figs. 1 and 2. The circumferential direction instrumentation is intended to capture local variations of temperatures with the progressive breakage of the conductor wires in the rupture section. On the other hand, the axial direction instrumentation had the objective to establish to what extent the effect of the increasing wire rupture may influence the conductor operation temperature.

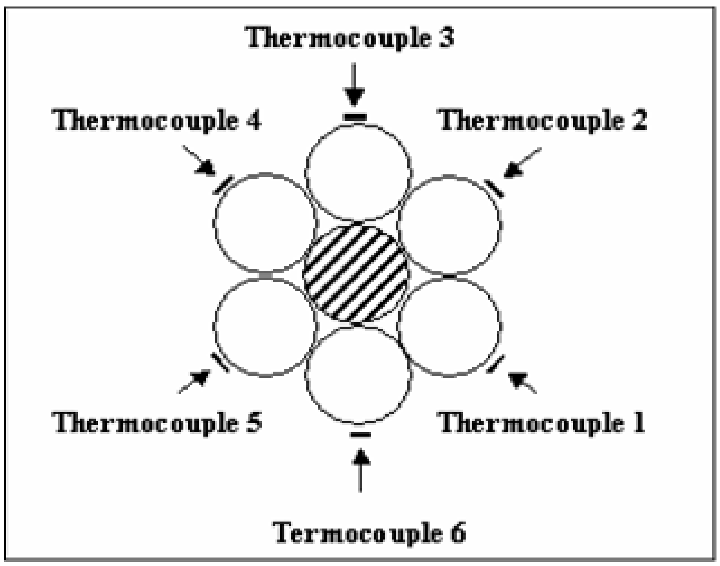


Figure 1. Test specimen rupture cross section and indication of the circumferential thermocouples

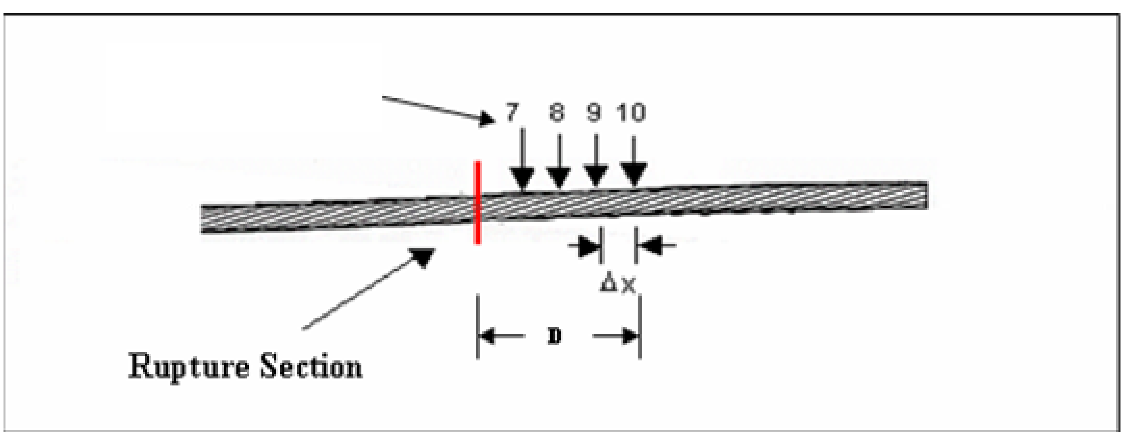


Figure 2. Test specimen rupture cross section and indication of the axial thermocouples

Table 1 presents the definition parameters of the instrumented test specimen, according to Figs. 1 and 2.

Table 1. Definition parameters of the instrumented test specimen

| Conductor | Penguin |
|---|---|
| Aluminum wires | 6 |
| External Aluminum wires | 6 |
| Steel wires | 1 |
| Lenght (m) | 2 |
| D (m) | 1 |
| $\Delta$x (m) | 0.15 |
| Number of thermocouples | 10 |

## 2.1. Circunferential instrumentation

As can be seen in Fig. 1, in the circumferential instrumentation thermocouples were externally attached to the wires along the circumference in the rupture section. The rupture sequence was defined from wire #1 to wire #5, since it was determined that wire #6 should not rupture to still allow electricity to be conducted by the Aluminum at the rupture cross section. Once wire #1 was selected before the test, all other wires were numbered in the counter-clockwise direction. The determination of the wire that will not rupture was important because it will keep conducting electrical current after all the wires were broken. The axial instrumentation was installed in this wire.

## 2.2. Axial instrumentation

As shown in Fig. 2 and Table 1, in the axial instrumentation the distance between the thermocouples was $\Delta x = 0{,}15$m. The total instrumentation length is then the sum of all distances $\Delta x$, and equals to D = 0,60m from the rupture section. The axial instrumentation was always positioned in wire #6, thus following a helicoidal pattern from the rupture section. Due to the symmetry of the problem, the axial instrumentation was attached only on one side of the rupture section.

## 2.3. Test conduction algorithm

The test was conducted according to the following steps:
(a) to instrument the test specimen (Figs. 1, 2, 3 and 4);
(b) to set up the system of data acquisition;
(c) to assemble the electrical circuit (Figs. 5 and 6);
(d) to turn on the source of alternating current and set it to 325 A (nominal operation current of the conductor);
(e) to wait for the system to achieve thermal steady state (variation of de ±1ºC in temperature of the $6^{th}$ wire);
(f) to perform the readings of the thermocouples;
(g) to break the $1^{st}$ Aluminum wire;
(h) to repeat the steps from (e) to (g);
(i ) to repeat the step (h) for the $2^{nd}$, $3^{rd}$, $4^{th}$ and $5^{th}$ wires.
The wire rupture was manually done using hand cordless drill and cut pliers.

## 2.4. Test equipment

The thermocouples used were from Labfacility XF-324-FAR, type K, with fiberglass insulation and accuracy of ±1.5°C. The thermocouples were attached to the wires using an insulation of mica between the thermocouple and the conductor for better results. Nylon standard clamps were then applied to the bundle to keep the instrumentation in place. Figures 3 and 4 show how the thermocouples were fixed in the test specimen.

The heating of the test specimen was performed by the electrical circuit shown schematically on Fig. 5. The circuit was composed by a Varivolt and Tension Regulator (Anel Varivolt and Tension Regulator, tension 440 V, power 50 kVA) to control the tension of the primary circuit. The primary circuit was connected to a Current Transformer through which the test specimen was passed in order to induce high current at low voltage, for safety reasons. The induced current was then monitored at the test specimen by the clamp-on ammeter (GE, 0 to 800A). This current delivered the energy necessary for the specimen heating. The system, pictured in Fig. 6, was started at the nominal operational conductor current (325 A) and controlled to maintain it throughout the test. Data was acquired along the test using the data acquisition system showed in Fig. 7 (Agilent Technologies 34970A, accuracy 0.004% and resolution of 6½ digits).

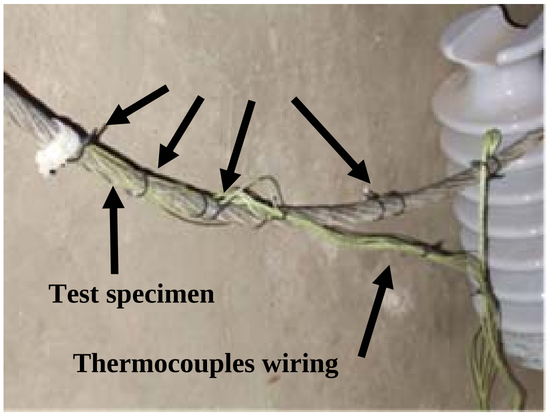


Figure 3. Specimen instrumentation

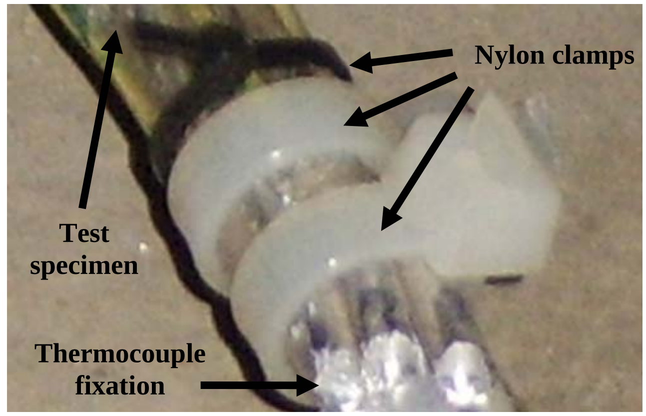


Figure 4. Nylon clamps and thermocouples fixation

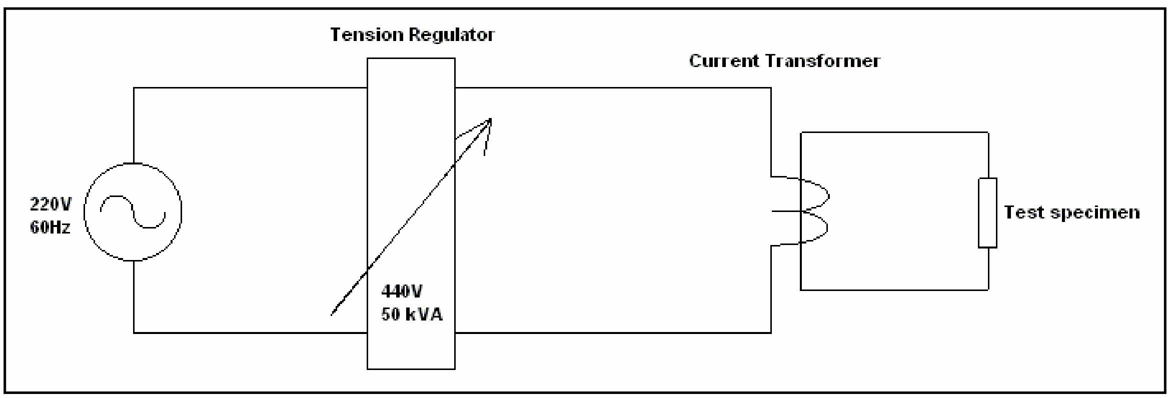


Figure 5. Test circuit

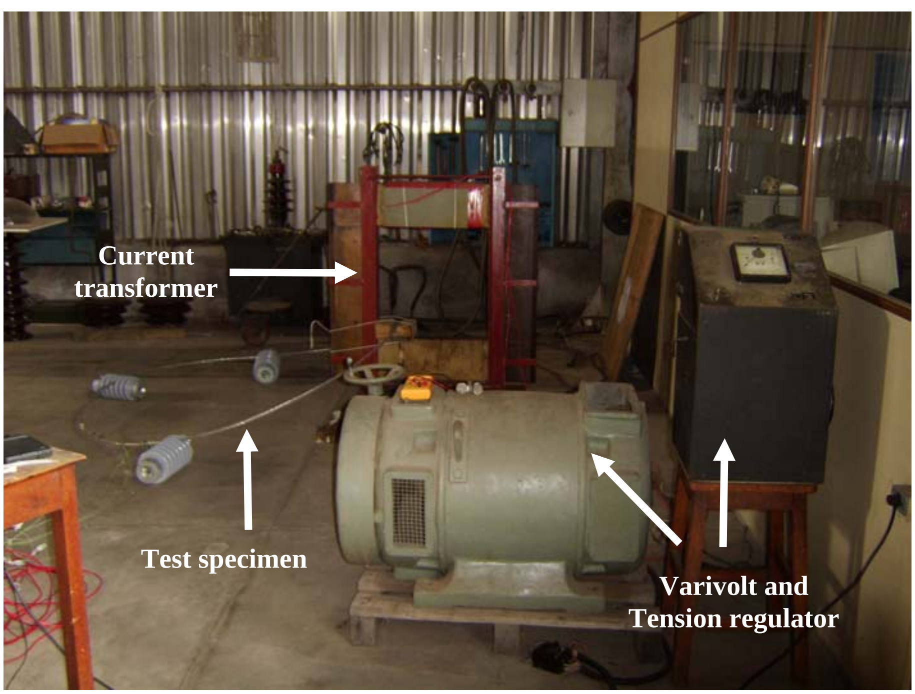


Figure 6. Test setup

Figure 7. Data acquisition system

## 3. RESULTS AND DISCUSSION

### 3.1. Test stages

The test conduction algorithm, described on section 2.3, was implemented and divided into stages defined on Tab. 2. Table 3 shows the temperature readings for these stages. Figure 8 shows the test specimen after the first Aluminum wire was cut. The stage 12 at Tab. 3 shows a temperature difference of 183°C between thermocouple #6 (300ºC), placed near the rupture section of wires and thermocouple #10 (117ºC) away from this section, clearly demonstrating that the rupture section temperature more than doubled the far field temperature, thus indicating the local nature of the problem.

Table 2. Summary of the test stages (beginning and ending of the stabilization of the temperature)

| Stage | Test Current (A) | Beginning | | | | Ending | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Timetable (hh:mm) | Elapsed Time (min) | Room Temperature (ºC) | Humidity (%) | Timetable (hh:mm) | Elapsed Time (min) | Room Temperature (ºC) | Humidity (%) |
| Full conductor | 325 | 13:45 | 0 | 28 | 70.4 | 14:14 | 29 | 29 | 62.9 |
| $1^{st}$ ruptured wire | 325 | 14:20 | 35 | 29 | 61.4 | 14:36 | 51 | 29 | 58.5 |
| $2^{nd}$ ruptured wire | 325 | 14:42 | 57 | 29 | 58.5 | 14:58 | 73 | 31 | 60.9 |
| $3^{rd}$ ruptured wire | 325 | 15:01 | 76 | 31 | 60.9 | 15:20 | 95 | 29 | 59.6 |
| $4^{th}$ ruptured wire | 325 | 15:25 | 100 | 29 | 59.6 | 15:40 | 115 | 30 | 60.8 |
| $5^{th}$ ruptured wire | 325 | 15:45 | 120 | 30 | 60.8 | 16:00 | 135 | 30 | 68.6 |

Table 3. Summary of the measured temperatures

| Stage | Summary of the measurement of the test temperature | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Elapsed Time (min) | Thermocouple | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 – Begin of the heating | 0 | 32 | 32 | 33 | 32 | 32 | 33 | 33 | 33 | 33 | 34 |
| 2 – Begin of the cut – $1^{st}$ wire | 29 | 95 | 93 | 94 | 96 | 99 | 99 | 94 | 92 | 94 | 98 |
| 3 – End of the cut – $1^{st}$ wire | 35 | 100 | 94 | 96 | 94 | 98 | 97 | 96 | 92 | 91 | 97 |
| 4 – Begin of the cut – $2^{nd}$ wire | 51 | 103 | 101 | 103 | 102 | 106 | 105 | 101 | 95 | 94 | 98 |
| 5 – End of the cut – $2^{nd}$ wire | 57 | 103 | 101 | 103 | 102 | 106 | 106 | 100 | 95 | 96 | 101 |
| 6 – Begin of the cut – $3^{rd}$ wire | 73 | 115 | 117 | 114 | 117 | 122 | 123 | 107 | 96 | 95 | 100 |
| 7 – End of the cut – $3^{rd}$ wire | 76 | 117 | 119 | 116 | 119 | 124 | 122 | 112 | 102 | 99 | 102 |
| 8 – Begin of the cut – $4^{st}$ wire | 97 | 138 | 139 | 134 | 142 | 150 | 155 | 130 | 107 | 99 | 100 |
| 9 – End of the cut – $4^{th}$ wire | 100 | 140 | 145 | 140 | 149 | 155 | 156 | 140 | 115 | 103 | 102 |
| 10 – Begin of the cut – $5^{th}$ wire | 115 | 165 | 175 | 168 | 183 | 201 | 205 | 175 | 138 | 118 | 113 |
| 11 – End of the cut – $5^{th}$ wire | 120 | 172 | 183 | 176 | 190 | 206 | 209 | 183 | 149 | 128 | 119 |
| 12 – Maximum temperature | 126 | 193 | 173 | 174 | 205 | 243 | 300 | 56 | 159 | 125 | 117 |

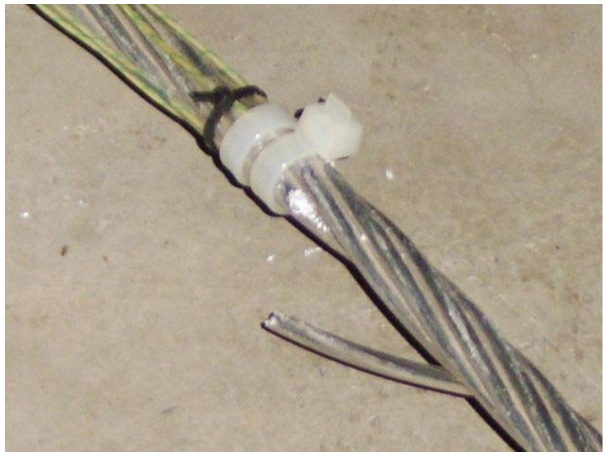

Figure 8. Test specimen with the 1st wire cut

As the test was developing, the increase in the temperatures promoted degradation not only on the nylon fixation clamps but also at the thermocouples insulation. This degradation eventually culminated in the failure of the sensor at the times showed on Tab. 4., which also shows the last temperatures measured by these sensors before failure. As it can be also seen on Tab.4, all sensors failed after the 5th wire was cut. Figure 9 shows the specimen after the 5th wire cut.

Table 4 – Summary of the failures of the thermocouples

| **Thermocouple** | **Test** | | |
|---|---|---|---|
| | **Elapsed Time (min)** | **Temperature (°C)** | **Stage** |
| 3 | 123.5 | 188 | 11 – End of the cut – 5th wire |
| 7 | 124.9 | 209 | 11 – End of the cut – 5th wire |
| 1 | 126.9 | 192 | 11 – End of the cut – 5th wire |
| 6 | 126.9 | 298 | 11 – End of the cut – 5th wire |
| 9 | 142.9 | 164 | 11 – End of the cut – 5th wire |
| 10 | 142.9 | 136 | 11 – End of the cut – 5th wire |
| 2 | 143.2 | 290 | 11 – End of the cut – 5th wire |
| 5 | 143.5 | 243 | 11 – End of the cut – 5th wire |
| 4 | 143.7 | 197 | 11 – End of the cut – 5th wire |
| 8 | 144.2 | 199 | 11 – End of the cut – 5th wire |

Figure 9. Test specimen after the 5th wire cut

### 3.2. Temperature of the Aluminum wires along the test

Figure 10 shows all stored data along the test, from the beginning of the heating of the test specimen to the removing of the thermocouples. It represents the temperatures as function of time for all thermocouples.

Figure 11 shows the temperatures reached by the thermocouples up to the $5^{th}$ wire was cut. It can be observed that at the $5^{th}$ wire cut, thermocouples #1, #3, #6 and #7 were no longer working (Tab. 4). Thermocouple #7 signal was completely lost, while the other 3 signals presented no significant temperature increment as the core temperature of the rupture section has increasingly risen. After that the thermocouples started to fail, according to Tab. 4.

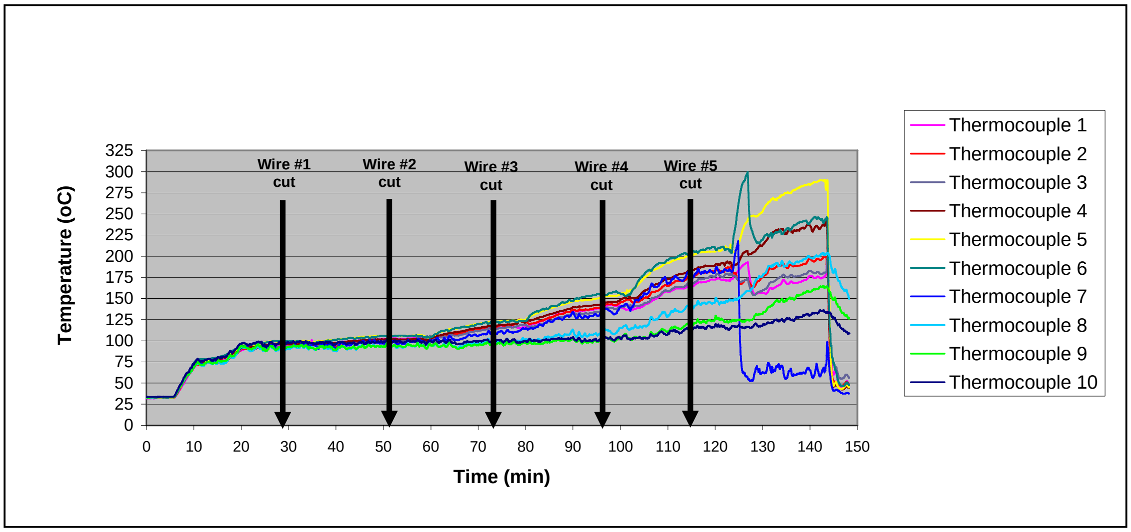


Figure 10. Temperature expressed as a function of time for all thermocouples along of test

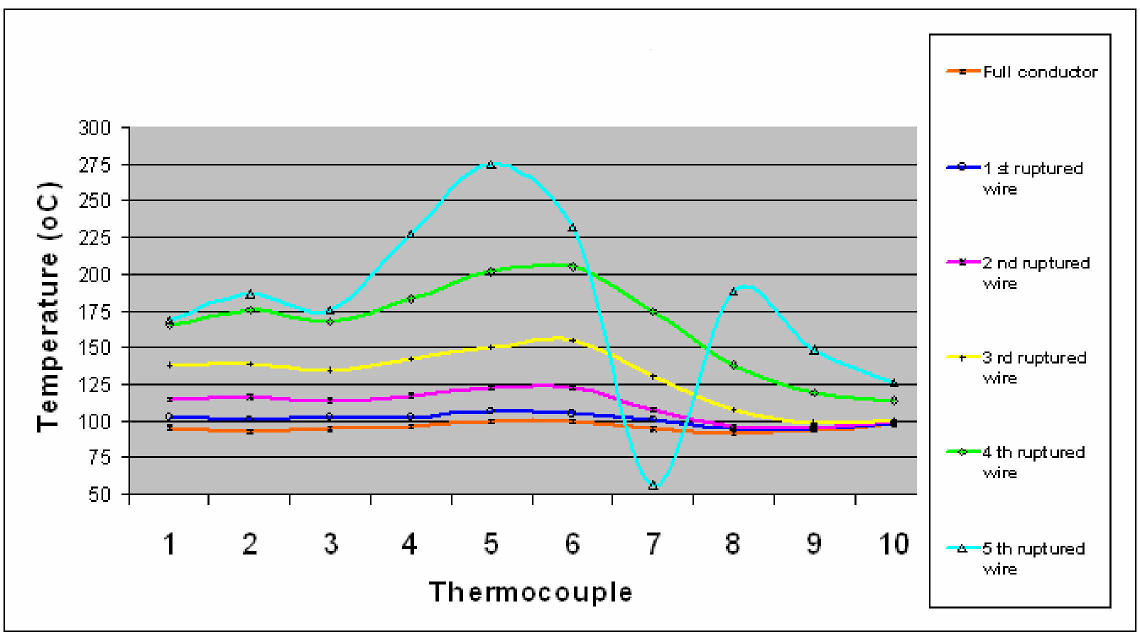


Figure 11. Maximum temperatures for selected stages up to $5^{th}$ wire cut

Figure 12 indicates the variation of the temperatures of the Aluminum wires along of different stages of the test, through of a pallet of colors, respectively to thermocouples #1 to #6 (circumferential) and #7 to #10 (axial).

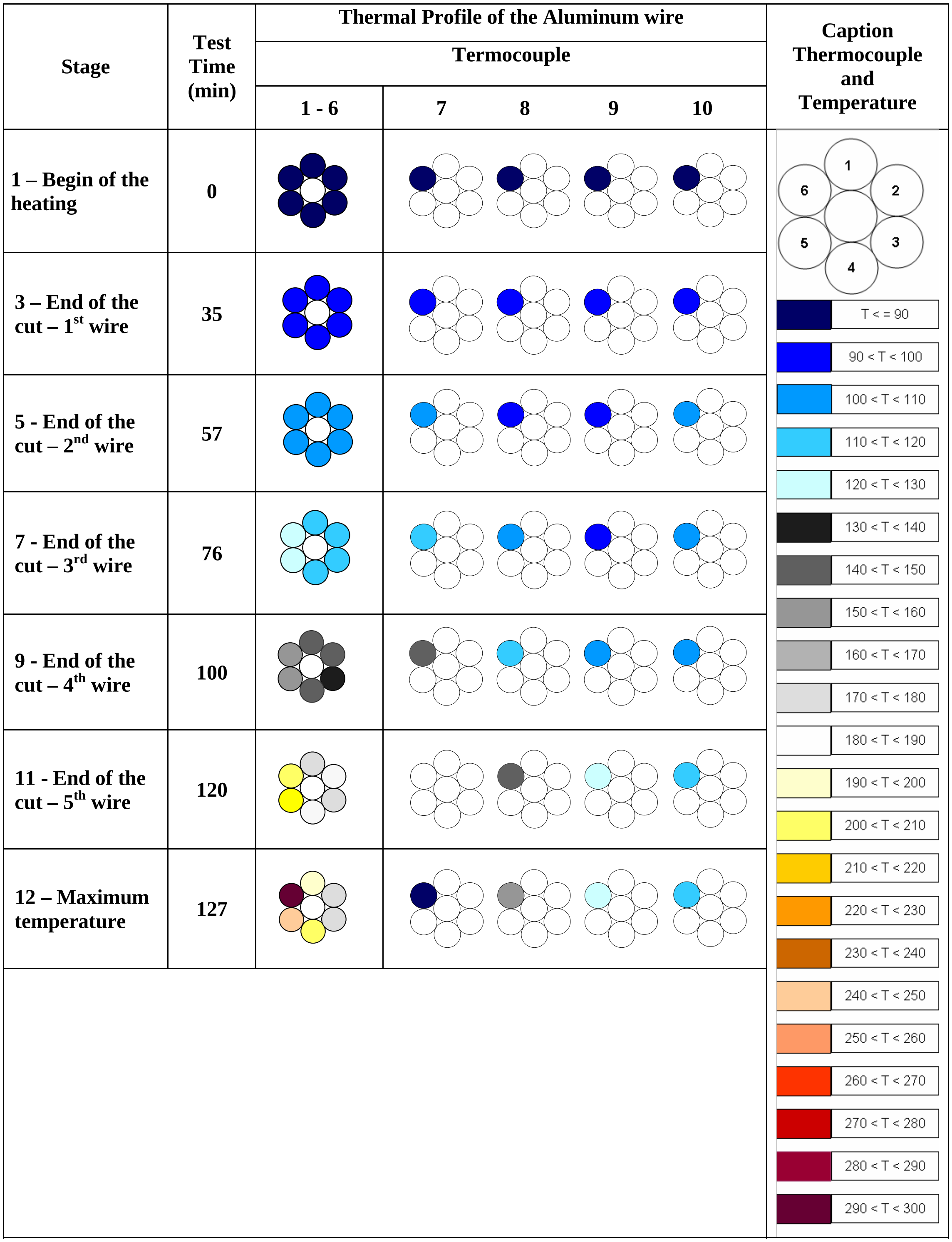


Figure 12. Temperature at each stage for thermocouples #1 to #6 along of test using a discrete palette of colors

The comparison of the thermal profile of the conductor with thermo graphic images obtained in overhead inspection of overhead transmission line (Fig. 13) could help the analysis of hot points in conductor connections, identifying, thus, the occurrence of rupture of Aluminum wires.

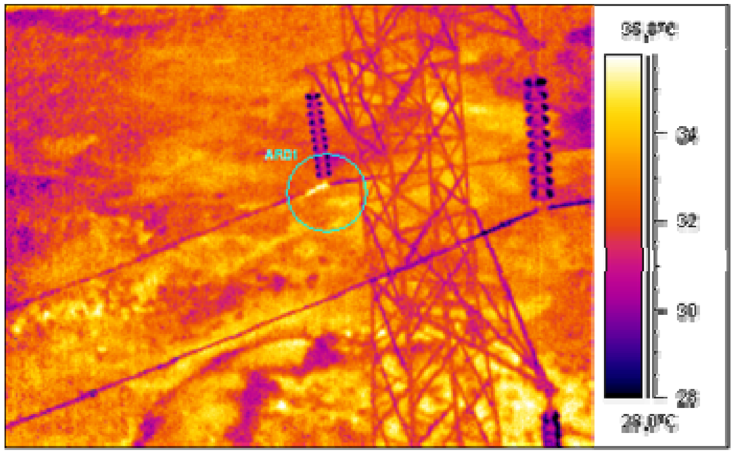


Figure 13 – Hot point detected during the overhead thermo graphic inspection (Resende, 2001)

### 3.3. Comparison of test results and Morgan predictions

Test results were compared with calculations using Morgan's methodology for the conductor temperature profile (Morgan, 1991). This methodology evaluates the conductor temperature by means of an energy balance calculation. The test was conducted in lab-controlled environment, which resulted in known parameters for calculating the temperature profile according to Morgan. The reduction of the Aluminum area in the cross section of the conductor due to progressive rupture of the wires and consequent increment on the conductor electrical resistance were considered in the calculation. The theoretical conductor temperature profile was then evaluated for the several stages of the test, in the same environment condition and electrical current. For comparison, conductor test temperatures were considered as the average of the measured temperatures of thermocouples from #1 to #6 for each test stage.

The comparison between the theoretical and experimental values is presented in Tab. 5 and Fig. 14. It can be inferred that the test temperatures for the conductor showed the same trend of temperatures calculated using Morgan's methodology. However, results from Morgan over-predict the temperature on the conductor, with increasing differences for increasing temperatures.

Table 5 – Comparison of the values between Morgan and average results of test

| **Stage** | **Test Data** | | | **Conductor Temperature** | | |
|---|---|---|---|---|---|---|
| | **Test Corrent (A)** | **Time (min)** | **Room Temperature (°C)** | **Morgan Calculated (°C)** | **Test Average (°C)** | **Error (%)** |
| 1 - Full conductor | 325 | 29 | 28 | 93 | 96 | -3.13 |
| 3 - 1st ruptured wire | 325 | 51 | 29 | 104 | 103 | 0.97 |
| 5 - 2nd ruptured wire | 325 | 73 | 29 | 123 | 118 | 4.24 |
| 7 - 3rd ruptured wire | 325 | 95 | 31 | 153 | 143 | 6.99 |
| 9 - 4th ruptured wire | 325 | 115 | 29 | 213 | 183 | 16.4 |
| 11 - 5th ruptured wire | 325 | 135 | 30 | 399 | N/A | N/A |

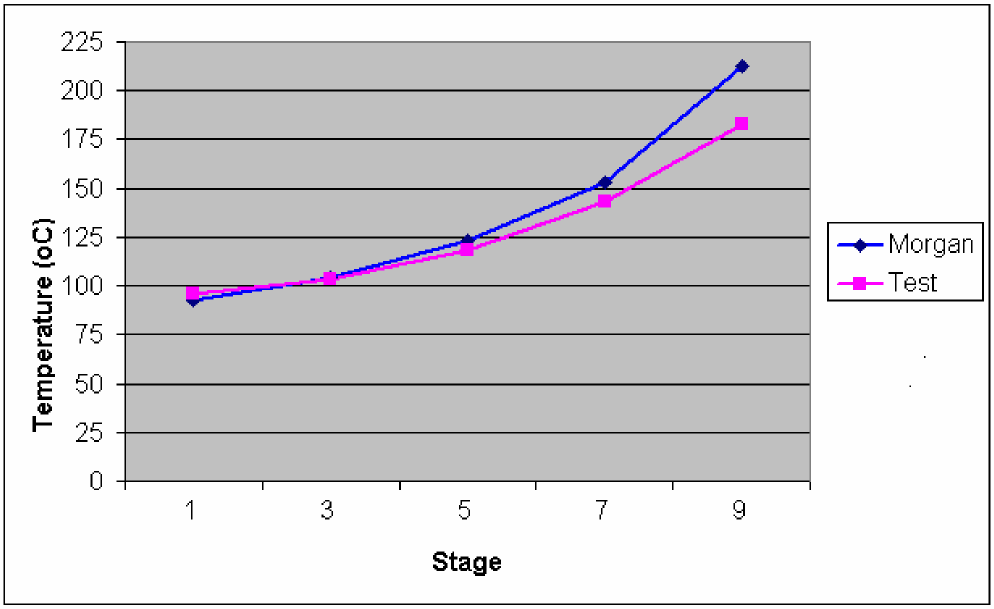


Figure 14 – Difference between theoretical and experimental temperatures (average)

## 4. CONCLUSIONS

In this work a test was performed to evaluate the temperature profile on an ACSR Penguin conductor in the event of progressive rupture of its Aluminum wires. Test results were then correlated to theoretical model predictions using Morgan's methodology. Relative difference between measured and estimated temperatures increased with temperature increase remaining, however, within the range of 20% error.

Results preliminarily indicate that the theoretical model might need some correction factors. However, new tests are necessary to obtain more accurate data, not only on the experimental end but also on measured controlled parameters used in the theoretical calculation. A larger number of thermocouples is desirable and their positioning and fixation should be modified in order to avoid signal loss for higher temperatures. Different types of conductors should be tested. Tests can also be coupled with simultaneous thermo graphic images for verification.

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