Thermal Testing and Analysis Techniques for Wires and Wire Bundles

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Abstract. Determining wire and wire bundle amperage capacity (i.e., “ampacity”) currently relies on the use of standards to derate wire ampacity when in a bundle configuration. The feasibility of developing physics-based and regression thermal models of single wires and wire bundles to determine ampacity using a customized test apparatus was investigated during a pathfinder study. A test facility was developed and various wire and wire bundle articles were tested under a variety of temperature and pressure conditions using an efficient test matrix formulated using Design of Experiments (DOE) techniques. Physics-based models were developed and correlated to the test results. Regression models were formulated and compared to test results and standards.

1. Background
The goal of this study was to assess the feasibility of developing thermal models of single wires and wire bundles. If successful, and ultimately matured and validated, these models could supplant reliance on current standards’ narrow tables to derate allowable current flow so as to prevent exceeding wire temperature limits due to resistive heat dissipation within the wires or wire bundles.

A wire bundle test apparatus was developed for measuring the temperatures of single wires and wire bundles. The test apparatus collected wire conductor temperature data under high vacuum and atmospheric conditions and varying environmental temperatures and currents for the two most common wire types used on spacecraft. Physics-based thermal models of single wires and wire bundles were developed and demonstrated. Predictions were validated by comparing analysis results with the experimental data. Test results also correlated well with published wire bundle derating standards [1] and [2]. In addition, a regression model was developed that could accurately predict the data.

2. Test
The test apparatus was developed to measure the temperature of a single wire or wire bundle carrying varying levels of DC electrical current in a controlled thermal environment. The apparatus was designed to simulate an infinitely long wire carrying a fixed current in a uniform thermal environment at steady state conditions. The test configuration consisted of a wire/wire bundle test article suspended in a temperature-controlled shroud within a pressure-controlled (i.e., vacuum) chamber. A DC power supply...
was used to control the amount of current flowing through the wire, while fine gauge thermocouples soldered directly onto the conductors measured wire bundle temperature. Shroud temperature and chamber pressure were monitored. A schematic of the system as well as the shroud internal configuration are shown in Figures 1a and 1b, respectively. Particular care was taken to ensure accurate environmental control and reliable measurement data. The test facility was capable of sustaining a vacuum of less than $1 \times 10^{-6}$ Torr and controlling shroud temperature from -50 °C to +75 °C with a maximum temperature differential of 5 °C across the shroud. The power supply providing current to the wire bundle had typical fluctuations of 1 mA. Maximum measurement errors were estimated to be ±5 °C for the bundle temperature measurement, ±0.1 A for the wire bundle current, ±$1.5 \times 10^{-8}$ Torr for the pressure, and ±2 °C for the shroud temperature.

![Figure 1.](a) Wire harness thermal test bed schematic, and (b) shroud interior with a wire bundle.)

Use of efficient Design of Experiments (DOE) methods to set up the experiment enabled combining the data in a single mathematical analysis, reducing the number of test runs required. The test matrix is available in the original report [3]. Changing current between each observation required only a turn of a dial and time for temperature to equilibrate. Changing chamber pressure and shroud temperature was more time consuming and was done only after several current changes. Changing test articles was the most time consuming operation and was performed after each test article went through several chamber pressure/environment temperature setting changes. Analysis of the data from this complex “split-plot” scenario as well as planning of the original test matrix was performed using JMP® software version 13.

3. Analysis

Physics-based analytical thermal models were developed for both single wire and wire bundle cases. For the single wire analysis (eqs. 1 and 2), key input wire properties such as resistance per unit length ($R_L$) at a reference temperature ($T_0$), the temperature coefficient of resistance ($\alpha$), and bundle geometry were measured directly. The single wire thermal model was a steady state heat balance expression including the effects of wire gauge (as measured by conductor and insulation jacket radius, $r_c$ and $r_j$, respectively), wire jacket material thermal conductivity ($k_w$), current flow ($I$), and, both, radiative (i.e., jacket emissivity, $\varepsilon$) and convective heat transfer ($h$) from the wire jacket [5]. Calculations were correlated to test data by adjusting an effective wire jacket infrared transmissivity ($\tau$) and, for atmospheric cases, a convective scaling factor ($f_h$). In eqs. 1 and 2, $T_c$ is the conductor temperature, $T_j$ is the jacket temperature, $T_e$ is the environment temperature, and $\sigma$ is the Stefan-Boltzmann constant.

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1 JMP is a registered trademark of SAS Institute Inc.
$I^2 R_{LS}[1 + \alpha(T_c - T_0)] = 2\pi r_s f h(T_s - T_e) + 2\pi r_s \sigma e(T_s^4 - T_e^4) + 2\pi r_c \sigma \tau (T_c^4 - T_e^4)$

(1)

$I^2 R_{LS}[1 + \alpha(T_c - T_0)] = \frac{2\pi k_{w}(T_i - T_o)}{\ln(r_i/r_o)} + 2\pi r_c \sigma \tau (T_c^4 - T_e^4)$

(2)

Forty-one cases were within 5 °C of test data, 3 were within 10 °C, and 4 within 18 °C. Results are summarized in Figure 2a.

Wire bundles were modeled using a thermal network and included the effects of wire gauge, number of wires in the bundle, wire jacket material, current flow, wire resistance as a function of temperature, wire-to-wire radiation and contact conductance, and radiative and convective heat transfer from the wire bundle exterior [3]. The thermal network model was solved for steady state conditions using the Systems Improved Numerical Differencing Analyzer (SINDA)$^2$ and correlated to test data by adjusting the wire-to-wire contact conductance and, for atmospheric cases, an external convective scaling factor. Nineteen cases were within 5 °C of test data, 6 were within 10 °C, and 2 within 13 °C. Results are summarized in Figure 2b.

Figure 2. Comparison of physics-based model and test data for (a) single wire, and (b) wire bundle.

A regression model was developed using test data resulting in an equation that can be used to predict any temperature within the range of currents tested and vice versa. A team member familiar with the aerospace wiring standard SAE AS50881G [2] noted that the relationship assumed in that standard included a term not for environmental temperature, but instead the log of the difference between the wire and environmental temperatures. Including this as a regression factor markedly improved the model. Best-fit regression equations$^3$ as a function of pressure, wire conductor temperature, shroud temperature, and American Wire Gauge (AWG) based on the test data and physics knowledge are presented in eqs. 3 and 4.

For Pressure = 0 (vacuum):

$\log_{10}(Current) = 1.0698 + 0.66227 \log_{10}(Wire\ Temp\ °C - Shroud\ Temp\ °C) - 0.012753 Wires\ per\ Bundle - 0.061764 AWG + 0.0012115 Wire\ Temp\ °C - 0.088395 (\log_{10}(Wire\ Temp\ °C - Shroud\ Temp\ °C))^2$

(3)

$^2$ SINDA by Cullimore and Ring Technologies, Inc.

$^3$ To reduce unnecessary rounding error in predictions, the coefficient terms have a seemingly high precision. It is recommended that predictions be rounded to nearest degree or 0.1 ampere.
For Pressure = 1 (atmospheric):

\[
\log_{10}(\text{Current } A) = 1.5006 + 0.52010 \log_{10}(\text{Wire Temp } ^\circ\text{C} - \text{Shroud Temp } ^\circ\text{C}) - \\
0.016792 \text{Wires per Bundle} - 0.061764 \text{AWG} - 0.0002630 \text{Wire Temp } ^\circ\text{C} - \\
0.006662 (\log_{10}(\text{Wire Temp } ^\circ\text{C} - \text{Shroud Temp } ^\circ\text{C}))^2
\]

(4)

The fit to the data was quite good. At 200 °C, the model overpredicted the test data by less than 0.1 A on average with RMS error less than 0.2 A. This equation could thus be used to predict ampacity of the wires in this test. The model is imperfect; as is, it assumes for instance that there is a smooth function between using one wire and a bundle of 32. It seems unlikely that this is the case, and that the true function may even be discontinuous. Nevertheless, the equation is at least illuminating and provides hypotheses for future testing. Bias between the regression model and SAE AS50881G’s Table 3 calculation for any particular condition depended on environment temperature and AWG. The range of biases was approximately ±1 A for single 20, 22 and 26 AWG wires at atmospheric pressure and environment temperatures between -50 and 200 °C. SAE AS50881G Table 3 tended to slightly underpredict single wire 200 °C test data. Though a rigorous comparison was not performed during this study, AS50881G predictions for the 32-wire data appear to be quite conservative as compared to test data. Additional information is available in reference [3].

4. Concluding Remarks

The results of the present study strongly support further model development and validation testing, which will allow the model to provide significant insight into wire bundle current carrying capacity design and to replace published wire derating standards. Based on limited testing and analysis conducted during this pathfinder study the assessment team concluded both the response surface model and physics-based thermal model developed during this assessment correlate with the pathfinder test data and single-wire estimates from SAE AS50881G.

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\(^4\) AS50881 is a trademark of SAE International.