Advances in Current Rating Techniques for Flexible Printed Circuits

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Abstract

Twist Capsule Assemblies are power transfer devices commonly used in spacecraft mechanisms that require electrical signals to be passed across a rotating interface. Flexible printed circuits (flex tapes, see Figure 2) are used to carry the electrical signals in these devices. Determining the current rating for a given trace (conductor) size can be challenging. Because of the thermal conditions present in this environment the most appropriate approach is to assume that the only means by which heat is removed from the trace is thru the conductor itself, so that when the flex tape is long the temperature rise in the trace can be extreme. While this technique represents a worst-case thermal situation that yields conservative current ratings, this conservatism may lead to overly cautious designs when not all traces are used at their full rated capacity. A better understanding of how individual traces behave when they are not all in use is the goal of this research.

In the testing done in support of this paper, a representative flex tape used for a flight Solar Array Drive Assembly (SADA) application was tested by energizing individual traces (conductors in the tape) in a vacuum chamber and the temperatures of the tape measured using both fine-gauge thermocouples and infrared thermographic imaging. We find that traditional derating schemes used for bundles of wires do not apply for the configuration tested. We also determine that single active traces located in the center of a flex tape operate at lower temperatures than those on the outside edges.

Introduction

Electrical power transmission across rotating interfaces (such as in SADAs) is typically accomplished using slip rings, twist capsules, or wire wraps depending on the degree of rotational freedom required by the application. Slip rings permit continuous rotation in either direction but can be expensive and complex, which can be considered a liability in terms of reliability in some cases. Some applications do not require continuous rotation and therefore can forgo slip rings in favor of the other, more cost-effective options listed above. While wire wraps can be very simple, they are also difficult to adequately characterize in terms of parasitic torque and life, with these parameters varying widely depending on many factors in the design. A much more common, more predictable, and higher reliability option is the twist capsule. This device makes use of flexible printed circuit tapes to carry the electrical signals between a rotor and stator. These tapes are typically constructed of a single-layer copper conductor layer sandwiched between layers of Kapton film using acrylic adhesive to bond the whole thing together.

A critical aspect to the design of any conductor in a space environment is the temperature rise in that conductor due to Joule (I^2R) heating; this is especially true for flex tapes used in twist capsules. The standard means for rating conductors in flex tapes has been to use nomographs derived from the electronics industry such as in MIL-P-50884. These techniques leave much to be desired, as experience has shown that in a vacuum the temperature rise in the conductors is highly dependent on the unsupported length of the flex tape. The heritage rating technique does not take this into account. A more physically representative technique was developed in the 1990's that took this length into account, and was based on a temperature-dependent finite-difference model (Hayes and Allen). This model has been used successfully for two decades, and has been tested and confirmed to be conservative in most cases. Results from a modified version of this model (modified to approximate radiative losses) are shown in

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Figure 1. What this model does not do is account for a duty factor in the flex tape itself, meaning that if only a portion of the traces in a tape are in use at full capacity the model must be factored without much engineering basis. This approach yields a robust design but not fully understanding some of these intra-tape thermal effects limit how far we can push the envelope in terms of current carrying capacity and unit density. We are currently involved in a program that is focused on a better understanding of these duty factor effects as well as a more complete model verification. For this paper, tapes were tested in a vacuum chamber using thermal imaging instruments and specialized view ports and chamber configurations.

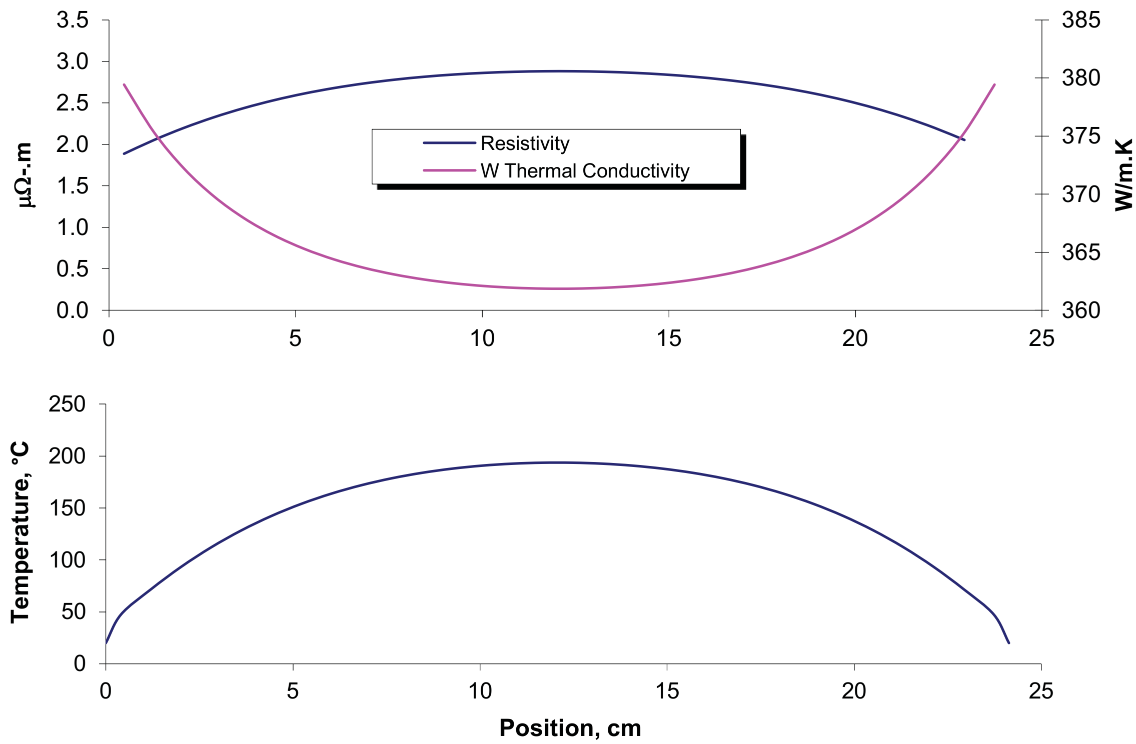

Figure 1. Example predicted temperature profile (bottom) and material properties (top) along the length of a flex tape in vacuum at 10A. In the case presented here the radiation has been added in order to approximate the test conditions in the experiments conducted. For a flight application, the radiative effect would be removed yielding a much higher temperature and therefore a lower suitable maximum current.

Experimental

A flex tape from a recent solar array drive flight application was used for testing (shown in Figure 2). Jumpers were soldered between the exposed solder pads at the ends of the tape in a “daisy chain” configuration so that a single power source could be used to energize all of the traces in series, but also allow for connection to individual traces using alligator clips.

The flex tape (construction details in Table 1) was mounted to an aluminum alloy support structure using low outgassing double-sided tape. Type K thermocouples (TCs) were attached using aluminum tape to each end of the flex tape where it contacted the aluminum supports, additional TCs were attached using aluminum tape to the aluminum supports themselves and to the chamber platen. Additionally a single fine-gauge type K thermocouple was attached using Kapton tape to the flex tape under test, near the center of the length and width of the tape; this was done to calibrate the thermographic camera. The chamber was pumped down and current applied to all traces of the tape, once stabilization had occurred a thermographic image was recorded of the region in which the TC had been attached. The emissivity setting in the camera was adjusted so that it indicated the temperature measured with the TC. Once this baseline was established, the mid-tape TC was removed.

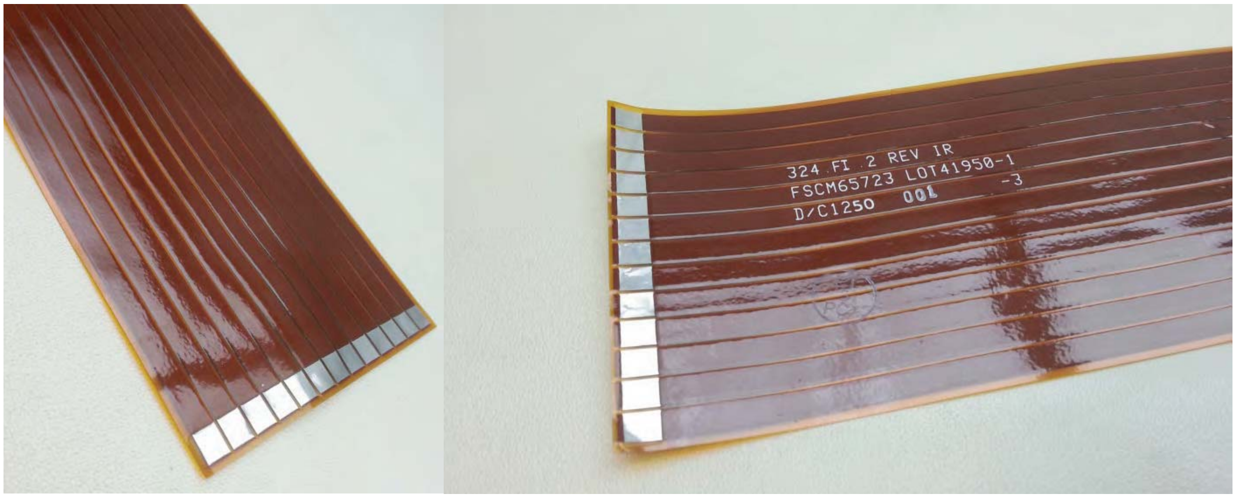

Figure 2. Flex tape used in tests.

A 40-mm-diameter CaF_2 window was used to view the tapes in far IR (where the FLIR operates). This material is transparent over most of the spectrum in that range. Calcium fluoride does not transmit all wavelengths in the far IR range with complete transparency, but since the previously described calibration procedure was performed thru the window we expect reasonable results.

Table 1. Construction details of the flex tape used in the testing performed here.

Parameter	***Value***
Overall Length	0.61 m (24 in)
Active Tape Length	0.24 m (9.5 in)
Overall Tape Width	0.061 m (2.4 in)
Number of Traces	13
Trace Width/Spacing	$4.2x10^{-3}$ m / $8.9x10^{-4}$ m (0.16 5in / 0.035 in)
Trace Thickness Material	$7.1x10^{-5}$ m (2 oz = 0.0028 in) Rolled Annealed Copper (IPC W7)
Tape Construction	Kapton/Acrylic Adhesive/Cu Single Layer

Power was supplied to the flex tape via a bench power supply. Current was monitored using a handheld DMM. Temperatures were monitored using handheld thermocouple readers. The thermographic instrument used was a FLIR i3. This FLIR unit was positioned above the IR window in the top of the chamber (Figure 4) using a ball vise.

For each test, the chamber was evacuated using a mechanical roughing pump to a pressure of approximately 0.13 Pa (1 torr) and power was applied. Tests were done with current levels ranging from 1 A to 11 A. The current used for the tests reported on here was 10 A in every case; this value was chosen because it gave good signal to noise ratio on the FLIR and allowed us to see more subtle variations in unpowered trace temperatures. The temperature of the tape was allowed to stabilize in order to approximate the steady-state condition and a thermographic image recorded, as well as the temperature of all thermocouples, chamber pressure, current and the thermal image data file were logged. The chamber was brought back to atmospheric pressure trace connections modified and the process started again.

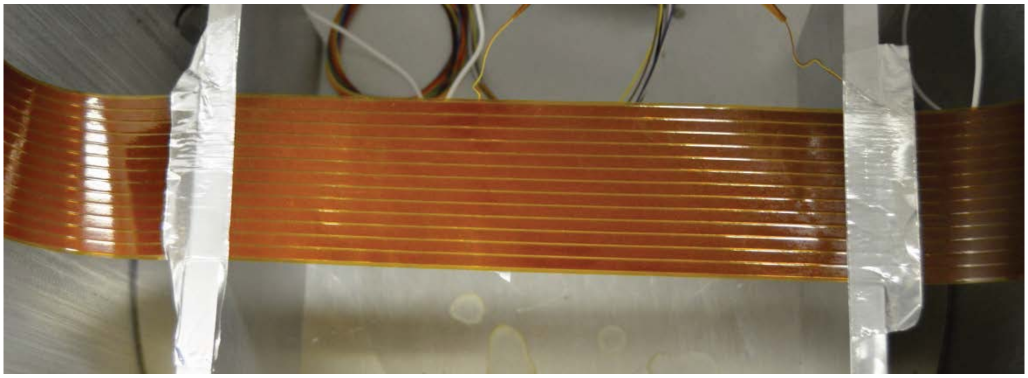

Figure 3. General tape configuration in chamber. The boundary temperature thermocouple can be seen on the right side of this photo.

Figure 4. Thermographic (FLIR) instrument positioned above CaF_2 port in top of chamber.

Results

FLIR images were translated to .csv files and then imported into Microsoft Excel for analysis. The output from the FLIR takes the form of a 60x60 matrix of temperatures. For the data presented here in Figure 6, a column of data near the center of the image was taken. The column number and method of extraction are consistent for all the results here. During periods of testing, a K-type thermocouple was attached to the exposed surface of the flex tape using acrylic adhesive Kapton tape, the temperature read was used to calibrate the FLIR by adjusting the emissivity input. The emissivity of the flex tape Kapton surface was found to be 0.37. No uncertainty was calculated for this result as the absolute value of the emissivity is not critical for this work. In all cases reported here, “temperature rise” indicates raw temperatures that have been modified by subtracting the aluminum support fixture temperature thereby negating any heating of the fixture and chamber.

A sample of image files from the FLIR are shown in Figure 5 where a photo of the flex tape is shown for reference and images from the cases where only trace #1 is powered, traces 1-7 are powered, and all traces are powered. In each case, 10 A is applied to every trace. Data like these were taken for 10 A applied to traces in the series 1, 1-2, 1-3 and so on until all traces were powered. Similar data were gathered for the cases where only trace 1 is powered, then only trace 2 and so on thru trace 6. These results are given in Figure 7.

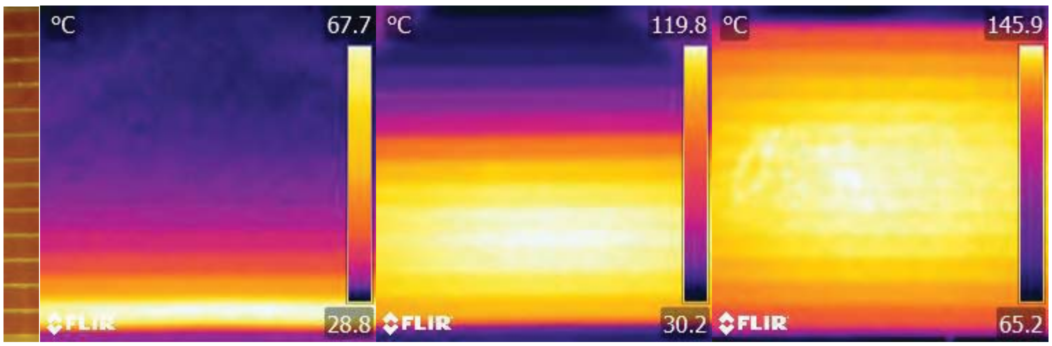

Figure 5. FLIR images of flex tape tests. Leftmost image is a photograph of a segment of the flex tape tested shown for context. The other images, left to right, are of trace#1 (bottommost trace) active, traces 1-7 active, and all thirteen traces active.

The numerical results from the series of images in Figure 5 are given in Figure 6. This graph shows the progression of the maximum temperature rise in the flex tape as more and more traces are energized. Here we can see that when three or fewer traces are energized near the edge of the tape the maximum temperature is less than the other cases. In every other case shown, the maximum temperature is relatively unchanged. This result is expressed in Figure 8 as a derating factor similar to those defined in MIL-STD-975.

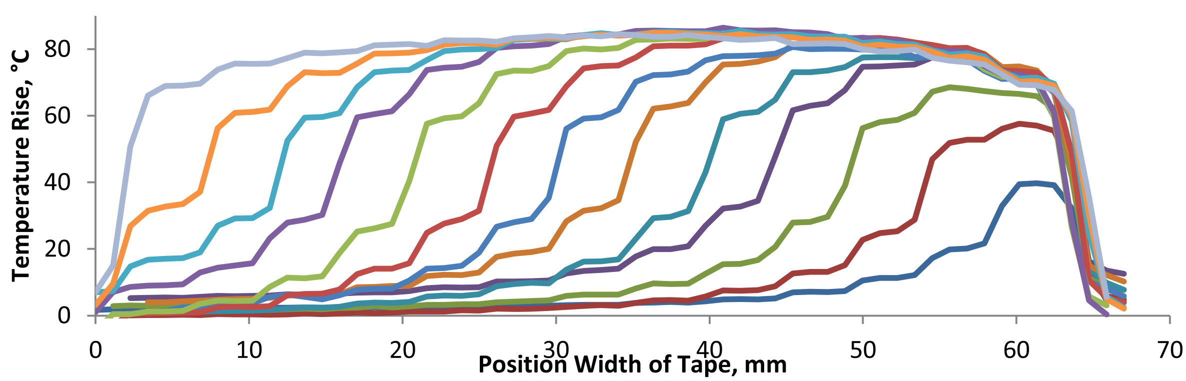

Figure 6. Temperature profiles across the width of the flex tape. Starting at the right side of the graph trace number one has 10A applied, the next data set is with two traces activated, and so on until all thirteen are active with 10A (corresponding to right-most image in Figure 5)

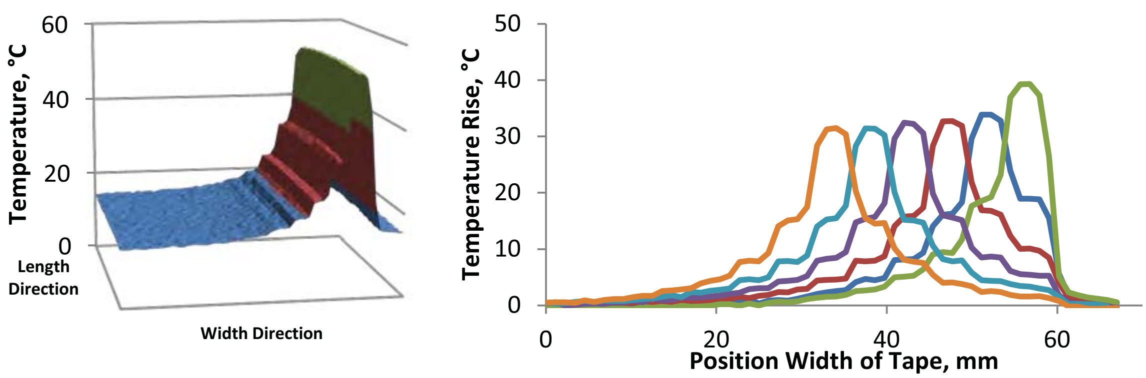

Figure 7. 3D plot of temperature output file from FLIR converted in Excel and corresponding to the single trace image in Figure 5. The graph to the right shows the results from individual, discrete loading of tapes 1-6 showing the more benign maximum temperatures associated with moving the active trace toward the center of the flex tape.

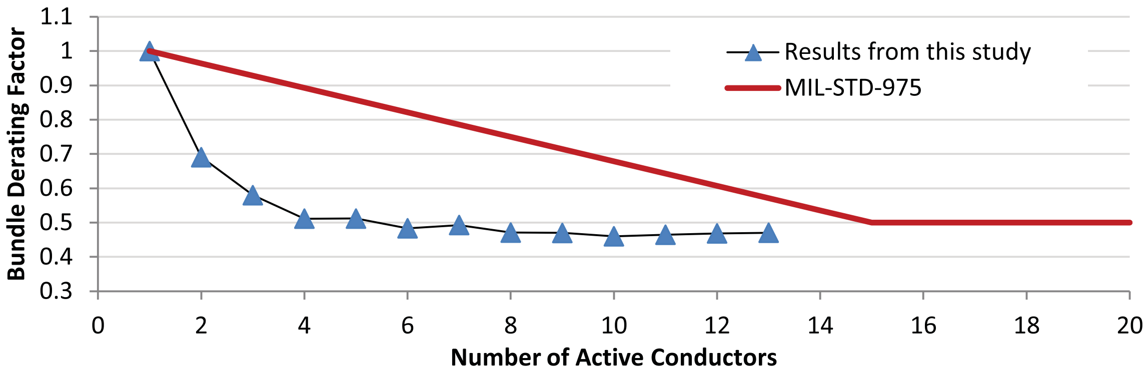

Figure 8. Results of trace loading tests (from Figure 6) represented as a derating factor and compared to MIL-STD-975.

Remarks and Conclusions

More work will need to be done in order to fully characterize and draw definitive conclusions about the thermal relationship between individual traces and their adjacent traces with flex tapes in other common configurations (trace widths, thicknesses and spacing) but for this particular tape we have found the following:

1. Radiative cooling of exposed (not wound into a twist capsule) flex tape can be substantial and the results of these tests, or any not done in a flight-like configuration, should be taken in context. Traces of the dimensions used in these tests should not be used at 10 A in a flight twist capsule configuration. In fact, for the application for which these particular tapes were designed and used the maximum current is 2.5 A per trace.
2. Interior traces run cooler than exterior traces. Those traces in the middle of the tape spread heat across several adjacent neighbor traces; those on the edges of a tape can only dissipate heat in one direction and can be several degrees hotter than equivalently loaded interior ones.
3. Traces on a single tape do not follow the rules for leadwire bundle derating per MIL-STD-975. Once more than three adjacent traces are fully loaded, the maximum temperature rise in the tape has reached its maximum, though placeing active traces on either side of a tape, keeping the middle for low power traces, should result in lower overall temperatures.

A practical application of conclusion 3 above is that the conservative current rating approach outlined at the beginning of this article can be modified for cases where the power traces can be allocated in groups of three or less. More work needs to be done with other flex tapes and rating models updated in order to determine how this relief should be applied.

References

1. Military Standard. “NASA Standard Electrical, Electronic, and Electromechanical (EEE) Parts List”, MIL-STD-975L, 31 January 1994.
2. Military Standard. “Printed Wiring Board, Flexible or Rigid-Flex, General Specification For”, MIL-P-50884E, 1 September 2010.
3. Hayes, Ron L and Blair R Allen. “Temperature-Based Current Derating of Monofilament Slip Ring Brush Wire for Space Applications.” *43rd International SAMPE Symposium and Exhibition*, Volume 43, May 31-June 4, 1998, pp. 1883-1893.