CABLE BUNDLE WIRE DERATING

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ABSTRACT

The allowable operating currents of electrical wiring when used in the space vacuum environment is predominantly determined by the maximum operating temperature of the wire insulation. For Kapton insulated wire this value is 200°C. Guidelines provided in the Goddard Space Flight Center (GSFC) Preferred Parts List (PPL) limit the operating current of wire within vacuum to ensure the maximum insulation temperature is not exceeded. For 20 AWG wire, these operating parameters are:

- 3.7 amps per wire
- bundle of 15 or more wires
- 70°c environment
- vacuum of 10^{-5} torr or less

To determine the behavior and temperature of electrical wire at different operating conditions, a thermal vacuum test was performed on a representative electrical harness of the Hubble Space Telescope (HST) power distribution system. This paper describes the test and the results.

BACKGROUND

The HST Power Distribution Units (PDUs) are the primary distribution points of electrical power for the HST electrical system. The PDUs accept high power, fused, solar array/battery power from the Power Control Unit (PCU), fuse this power into lower current services, and distribute it to all the HST loads.

The output services from the PCU use either 16 AWG or 20 AWG wiring, depending on load requirements that were set two decades ago. The wire used within the PDU is Kapton-insulated, multistranded, silver-coated copper wire. The maximum temperature for this kind of wire is 200°C, set by the insulation. (Connections are either crimped, or are heat-sunk such that the connections remain well below the melting temperature of solder, 183°C.) The specification for the wire is MIL-W-81381/17-20-4.

A recently proposed design modification would increase to as much as 6.0 Amps the current through a section of an individual 20 AWG wire; there are four such wires in a bundle of 28 wires. This produces a possible conflict with the GSFC Preferred Parts List

(PPL). The PPL specifies that the maximum current through a single 20 AWG wire be 3.7 Amps when that wire is present in a bundle of 15 wires or more, in a vacuum, and in an environment whose ambient temperature is 70°C.

However, the PDU wiring of concern is operating in an environment whose nominal temperature is 12°C, and whose maximum temperature is 25°C: not 70°C. In addition, most of the other wires in the bundle (24 of the 28) will be carrying no more than 3 Amps at any time: not all 28 wires will be simultaneously loaded to 6.0 Amps. Thus, it is not clear that the recommendation of the PPL applies, since it is clear that the precise conditions do not apply. Other guideline documents were also consulted, but offered no clear guidance. Finally, estimating the temperature rise using a radiative transfer model is not an option since neither the surface emissivity of these wires, nor the heat current coupling between the wires, are known to the required accuracy.

To determine if the operating conditions described above will present a potential failure point, or even a hazard, a thermal vacuum test was performed under conditions designed to match the actual operating conditions to the greatest extent possible.

TEST SET-UP

A bundle was constructed using the same wire and assembly procedures that had been used to construct the PCU bundle. In particular, the Kapton insulation was matched in color, to match the radiative properties of that used in the PCU bundle. The bundle is two feet in length, and contains a total of 28 wires. One wire was zigzagged back and forth to create the "background" bundle of 24 wires, and another wire was zigzagged to create the four "foreground" wires of present interest. This arrangement ensured that the same foreground current passed through each of the foreground wires, and the same background current passed through each of the background wires.

Four thermocouples were used, located about every six inches along the bundle, but no closer than six inches from either end of the bundle. These were type T thermocouples, with 30 AWG wire diameter. Each thermocouple was placed next to a selected wire being measured, and fastened with lacing cord. To provide a measure of the bulk temperature of the wires being measured, 7 mil aluminum tape was wrapped around the bundle and the thermocouple. A Kapton tape over-wrap of the aluminum tape was provided to maintain the thermal properties similar to the Kapton wire insulation. Two thermocouples were fastened to an outer wire (background), and two were fastened to an inner wire (foreground).

The wires were collected into a bundle so that each wire retains its relative position radially within the bundle, as one moves from one end to the other. (The wires were not "woven" into a braid or a rope.) In particular, the foreground wires are at (or near) the radial center, everywhere from one end of the bundle to the other. Cable ties were used every four inches along the bundle and tensioned using a Panduit Tie-Wrap tool with a setting of 4. The bundle was placed into the thermal chamber, in a nearly vertical orientation; thus, the thermocouples are classified as "top" and "bottom" in the table, rather than "left" and "right."

Figure 1 shows the test set-up and the schematic location of the thermocouples.

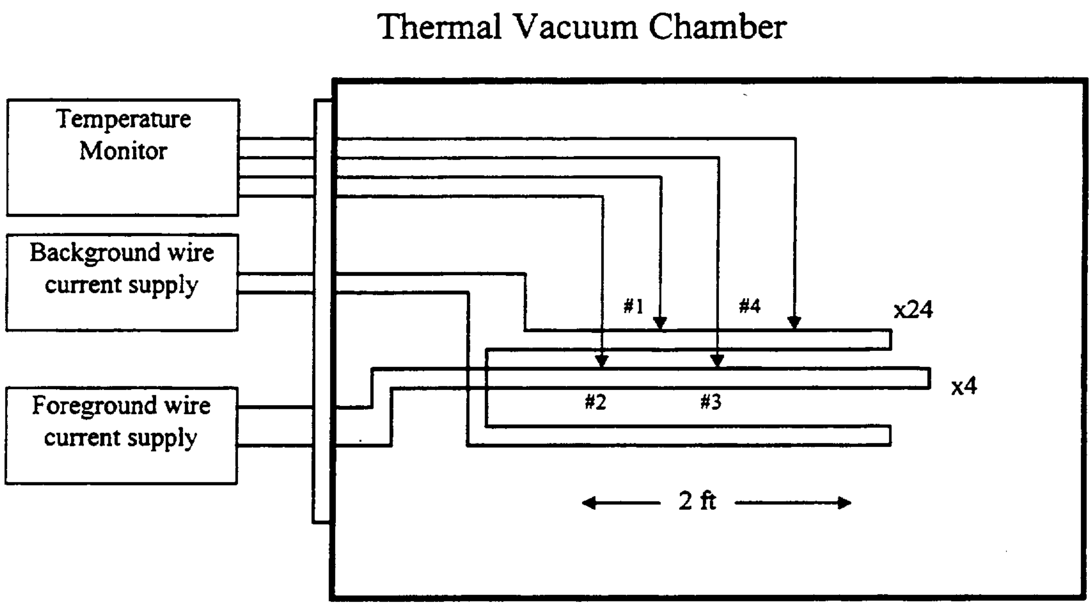

Figure 1 – Thermocouple Locations During Thermal Vacuum Test

Note: The figure depicts the wires installed in the thermal vacuum chamber in a horizontal configuration. This is for ease of drawing only. The wire bundle was actually installed in the thermal vacuum chamber in a vertical configuration as shown in Figure 2.

Figure 2 displays a photograph of the set-up in the thermal vacuum chamber.

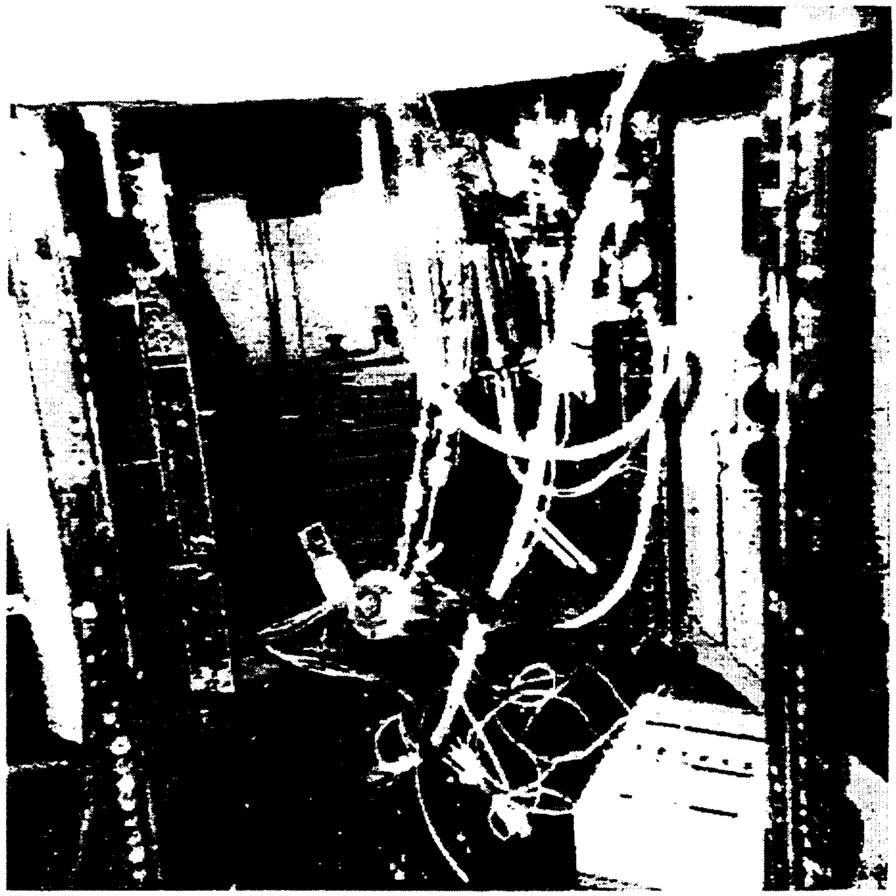

Figure 2 – Photograph of Thermal Vacuum Chamber

TEST RESULTS

The effects of three parameters were measured: the temperature of the thermal vacuum chamber's shroud, the foreground current driving the 4 wires of special interest to this study, and the background current driving the 24 enclosing wires.

Values were set and then held constant for each of these parameters until the steady state temperatures could be estimated. The values of the parameters, and the history of the four temperatures, are shown in Figure 3. Inspection shows that these temperatures approach steady state values for each set of test parameters, with a time constant (the time to achieve ~70% of the steady state value) of about 15 minutes. Estimates of the steady state values are given in Table 1.

Thermocouples #1 and #4 measure apparently equivalent locations: we would expect their temperatures to be identical except for differences in the construction of the bundle. We would expect the same from thermocouples #2 and #3. In fact, the difference T(#1)-T(#4) ranges from 5°C to 27°C, and the difference T(#2)-T(#3) ranges from 1°C to 6°C.

Cylinder Temperature °C	Background Current Amps	Foreground Current Amps	TC #1 Outside Top	TC#2 Inside Top	TC#3 Inside Bottom	TC#4 Outside Bottom
0	1	4	18	32	31	13
0	1	6	38	68	65	32
0	1	8	61	113	108	38
0	3	4	56	73	71	41
0	3	6	71	104	100	49
0	3	8	92	147	141	63
12	1	4	29	44	41	22
12	1	6	44	76	71	32
12	1	8	67	121	116	46
12	3	4	63	80	78	49
12	3	6	77	111	107	57
12	3	8	97	152	147	70
25	1	4	39	54	51	33
25	1	6	53	85	81	42
25	3	6	85	119	115	65
25	3	8	105	160	155	78
70	3.7	3.7	122	140	137	109

Table 1 – Experimental Data

The temperature of individual wires is affected by the extent of "openness" versus "tightness" of the bundle, which affects the thermal coupling of the individual wires. This effect is more important for wires on the outside of the bundle than for wires in the inside. We are most interested in the temperature of the inner wires, and these are well determined for our present purposes. We shall use the averages of thermocouples #1 and #4, and of #2 and #3.

To the extent that the properties of the wires do not depend on temperature, and that the temperature differences between the outer wires and the shroud are relatively small (on an absolute temperature scale), then the temperature increases above the shroud's temperature should be the same for each shroud temperature. Table 2 displays the foreground temperature (computed as the average of thermocouples #2 and #3), minus the temperature of the shroud.

Foreground Current	Shroud Temperature °C	Foreground Wire Temperature Minus Shroud Temperature For Background Current °C	
		1 Amp	3 Amp
4 Amp	0	32°C	72
	12	31	67
	25	28	---
6 Amp	0	67	102
	12	62	97
	25	58	92
8 Amp	0	111	144
	12	107	138
	25	---	133

Table 2 – Experimental Data With Shroud Temperature Dependence Removed

The entries in each box are in the vertical order: T(shroud) = 0°C, 12 °C, and 25 °C, respectively. Also, "---" means that the parameters were not included in the test. To a first approximation, the values do not depend on the temperature of the shroud. To a second approximation, there is a clear (if small) downward trend with increasing shroud temperature. This is caused in part by the temperature dependence of the electrical resistance of the wire, and in part by end effects, which, while small, are not completely absent. The 12 °C shroud temperature values are fit with an average error of about 5% by the expression

$$T_{Foreground} = T_{Shroud} + \frac{1.5°C}{Amp^2} * I_{foreground}{}^2 + \frac{4.8°C}{Amp^2} * I_{Background}{}^2$$

which has the expected theoretical form. On the one hand, this equation, with just two parameters, usefully summarizes 16 test results. On the other hand, a better fit would capture the dependence on the shroud's temperature: inspection of Table Two shows that the coefficients drop steadily with increasing shroud temperature. This would introduce other parameters, perhaps only one more, if the main dependence is caused by the change of resistivity with temperature (which is the same for both foreground and background wires).

The coefficient of the background current is larger (3.2 times larger) than the coefficient of the foreground current. There are 24 background wires, and 4 foreground wires (a factor of 6 times more); but the foreground wires are more tightly coupled to each other than to the typically more distant background wires, and this reduces the effect of the background wires on the foreground wires. Thus, the observed ratio of the current-coefficients is plausible.

The thermal vacuum test included the special case I(foreground) = I(background) = 3.7 Amp. This was not included in data set used to obtain the fitted expression. Using the expression, we compute T(foreground) = T(shroud) + 86°C, while the experimental value is 69°C. The computational value is 17oC, or 25% greater than the observed value. This difference would decrease sharply if the decrease of the coefficients with increasing temperature were to be included, since the coefficients represent the behavior at 12°C, and this last test used a shroud temperature of 70°C.

The test results show that the recommendation of the PPL keeps all wires under their rated maximum temperature, as it should.

The values of the coefficients of the fitting equation must depend on the emissivity of the insulation, and so must not be used to predict the behavior of other sorts of wire. It might prove possible to usefully estimate this effect, so that an approach like this one could be used to compliment guidebook recommendations. The form of the fitting equation should be general: the temperature rise of any wire above that of the shroud must be a linear combination of the squares of the currents through the other wires.

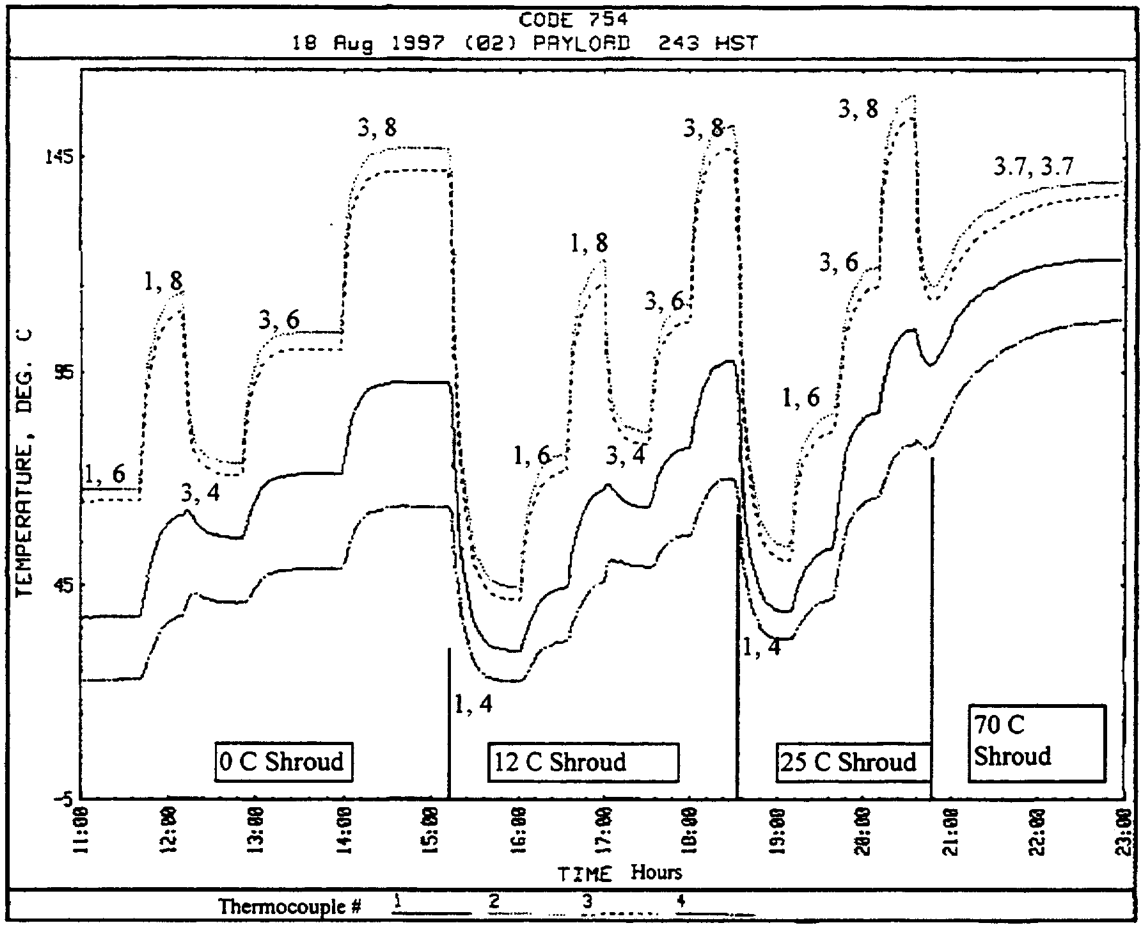

Figure 3 – Wire Bundle Temperature History

Notes: The numbers in the figure are the currents carried by the foreground and background wires. The first number is the background current: the current carried by 24 wires in the test bundle. The second number is the foreground current: the current carried by 4 wires in the bundle. For example, "3, 8" designates 3 Amps on the 24 background wires, and 8 Amps on the 4 foreground wires.

CONCLUSION

There is a high level of confidence that the wires within the PDU of the HST will not exceed or approach their maximum operating temperature. This is true even when as much as 8 Amp is passing through the subject wires, if no more than 3 Amp is passing through the remaining wires, and the PDU is no hotter than 25°C.

Under the conditions named in the PPL, some wires reached a maximum temperature of 140°C, which is safe.

A variety of test data were brought under the control of a single equation with two parameters. The form of this equation is general, and should apply to other wire bundles as well. Experiments are presently required to determine the parameters.