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Screening of Flexible Cables by Nonlinear Resistance Measurements

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13. ABSTRACT (*Maximum 200 words*)

Two traces in flexible cables used in the Milstar agile beam antenna system failed during acceptance testing. The cables, essentially printed circuit boards fabricated on flexible substrates, are composed of copper-foil conductors sandwiched between insulating Kapton layers. The cables carry current pulses used in the steering circuitry for the antenna beam. Upon sectioning and inspection of the suspect cables, substantial thinning of the copper foil conductors at feedthrough connections was noted. Other cables examined also exhibited thinning of metallization. Cables with degraded metallization develop anomalously high electrical resistances or can fail "open."

The difficulties encountered with these cables resulted from poor workmanship, and the cable manufacturer subsequently lost certification from the Defense Electronics Supply Center. However, a large number of the cables had already been installed in satellites, and the reliability of the cables is critically important to mission success. A considerable effort was, therefore, mounted by the contractors, with the support of Aerospace, to assess the extent of the problem and determine whether a suitable screening procedure could be developed so that only selective, rather than total, replacement of the cables installed on the first Milstar satellite, DFS 1, might be necessary.

In the course of this investigation, a screening test based on nonlinearities in cable resistance was developed. This test was originally intended to be applied to the cables in flight hardware. In fact, the application of this test to cables still in stores uncovered additional defective cables and led to a decision to replace all flexible cables with those from another manufacturer. This report documents one aspect of the flexcable investigation—the use of nonlinear resistance measurements for reliability screening. The test method itself is of general interest and could be further developed and incorporated into the specifications for testing of flexible cables and other components.

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PREFACE

This report has concentrated on one particular facet of the flexcable problem. Many people, both from the contractor organizations and from The Aerospace Corporation, contributed to the overall investigation of the flexcables. Don Schmunk of the Milsatcom Division headed the investigation for the Milstar program office and encouraged and facilitated the work. Otto Hinklemann of TRW was closely involved with all phases of the effort. He was on hand for the initial laboratory verification studies at Aerospace and also worked with EMS, Inc. as they developed their capability to make nonlinear resistance measurements. Wyman Williams of EMS, Inc. took the lead in the work in Atlanta.

Brent Morgan of the Electronics Technology Center (ETC), Technology Operations (The Aerospace Corporation) constructed much of the test equipment and made a number of the experimental observations. Don Mayer, Michael Tueling, and Denise Leung of ETC prepared test coupons for the laboratory investigation. Steven Robertson, then in the Electronics and Sensors Division at Aerospace, participated in the interpretation of the metallographic cross sectional analyses. Robert Ferro, also in the Electronics and Sensors Division, carried out analyses of the electrical resistance and thermal time constant of flexcables. Arthur McClellan, Electronics and Sensors Division, and Enold Pierre-Louis of the Vehicle and Control Systems Division, estimated cable lifetimes under various conditions of thermal and mechanical stress using finite element analysis.

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FIGURES

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I. INTRODUCTION

Two flexible cables (commonly referred to as "flexcables") used in the Milstar agile beam antenna system failed during acceptance testing. Many flexible cables of various lengths and configurations were already installed in the antennas in flight hardware. The situation with respect to the first satellite in the Milstar constellation, DFS 1, was of greatest concern. Replacement of all of the cables was one option, but would have involved considerable expense. Cable replacement requires disassembly, rework and reassembly, and retesting. These procedures all involve certain risks associated with the handling of components. Replacement of cables on DFS 1 with cables from the later satellites was discussed, as was the acquisition of new cables from a different manufacturer. The manufacturer of the suspect flexcables, Protosystems, had discarded the records and test coupons which must be retained with "class S" certified cables. These records need only be retained for three years. Traceability of the cables had therefore been lost. An investigation was initiated by the contractor, TRW, to determine the cause of the failures and to attempt to assess the extent of the "flexcable problem". Aerospace was an active participant in the investigation, with support provided by the program office and by personnel from the Electronics Technology Center (ETC) and the Systems Effectiveness Subdivision.

The possibility of *in situ* screening of cables installed in the flight hardware was a matter of particular interest. It was hoped that the development of a procedure for accomplishing such testing could have precluded the necessity for replacement of all of the installed cables. A very effective screening test based on nonlinearities in the cable resistance was actually developed. The test was sufficiently sensitive to reveal more unacceptable cables in stores at the antenna sub-contractor's facility (EMS, Inc., Atlanta, Georgia). The discovery of these additional bad cables led to a decision to replace all installed cables. The nonlinear resistance method itself worked well in this particular application. The method is of more general interest and potentially broader applicability. The results of the ETC investigation are summarized in this Technical Report both to document a part of the overall flexcable investigation and to provide a description of the nonlinear resistance technique itself.

II. BACKGROUND DISCUSSION

A. FLEXCABLE CONSTRUCTION

The cables in question are essentially printed circuit boards built on flexible rather than rigid substrates. "One ounce" copper foil traces are sandwiched between Kapton insulating layers. "One ounce" copper foil weighs one ounce per square foot, which is equivalent to a thickness of .0014 in. In addition to signal and return traces, the flexcables also incorporate some shield traces over the signal traces. A typical flexcable is illustrated in Figure 1.

These cables carry current pulses in the antenna switching circuitry. In the cable shown in Figure 1, the current paths are from the pulse driver connections at the upper right to the connections at the lower left. As indicated, the flexcables incorporate several metal layers. Connections to different layers of the cables are made by metal pins at "feedthroughs". The topography of the cables is shown in more detail in Figure 2, in which the insulating kapton layers have been omitted for clarity. A typical signal path is indicated by "X-X". The feedthroughs are the regions of primary interest in this investigation. A feedthrough hole is shown in a cross-sectional view in Figure 3. After a hole is made through the cable, a coating of electroless copper is applied first. The thin layer of electroless copper is then built up in thickness by an electroplating process. The copper provides good electrical contact to the foil layers of the cable. Metal contact pins are soldered into the plated through holes to provide external connections.

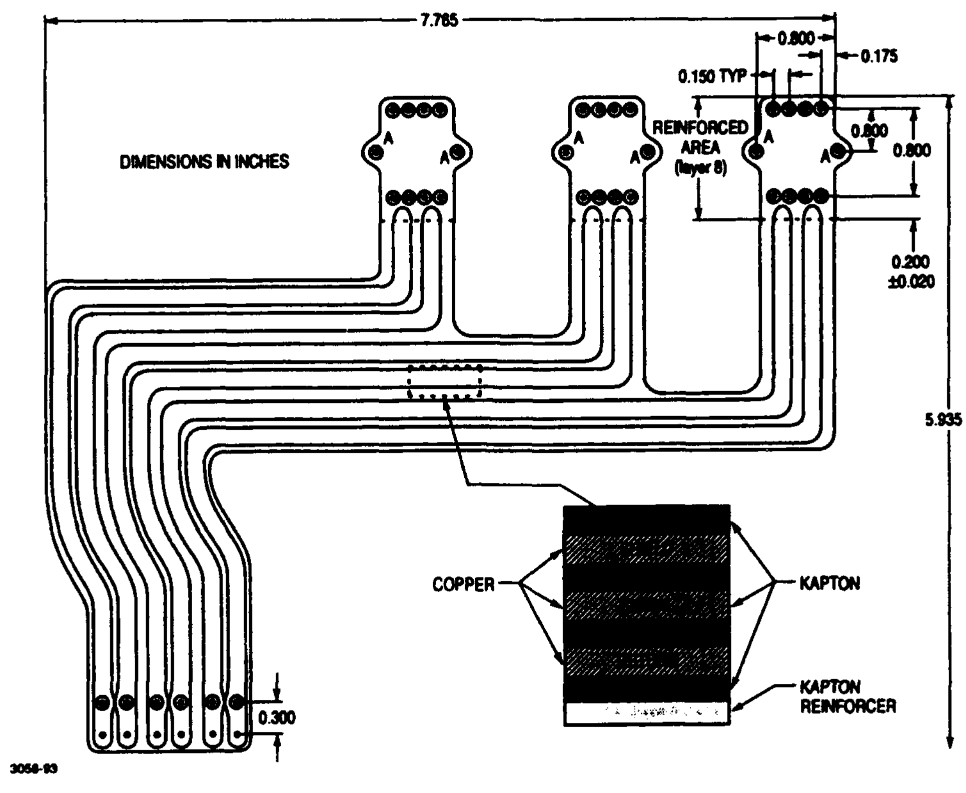

Figure 1. Layout of typical flexcable assembly. Inset illustrates structure in cross section.

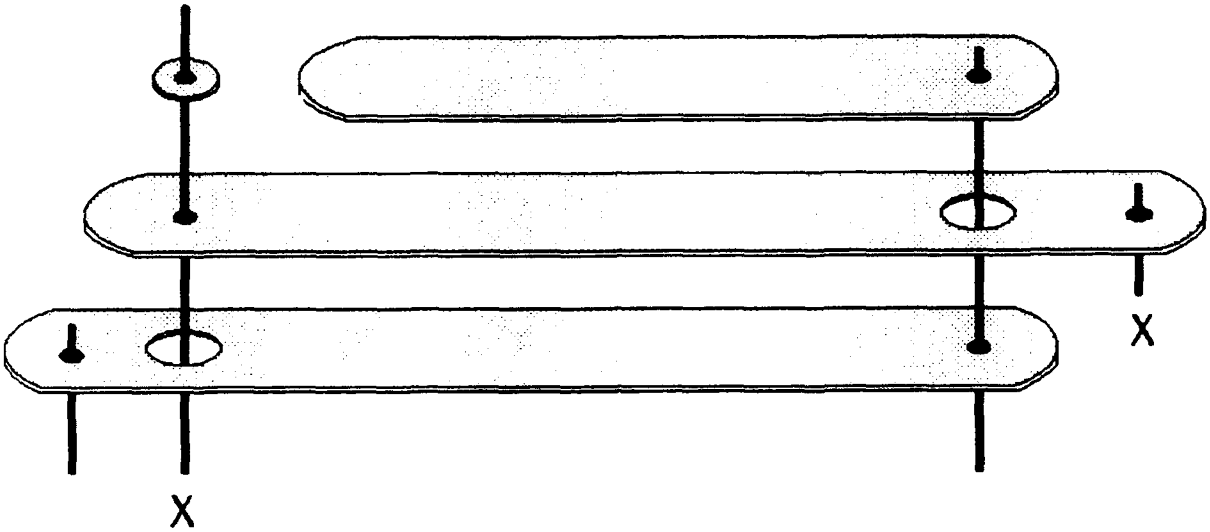

Figure 2. Cross section of flexcable showing typical metal signal path (X-X). Insulating Kapton layers have been omitted.

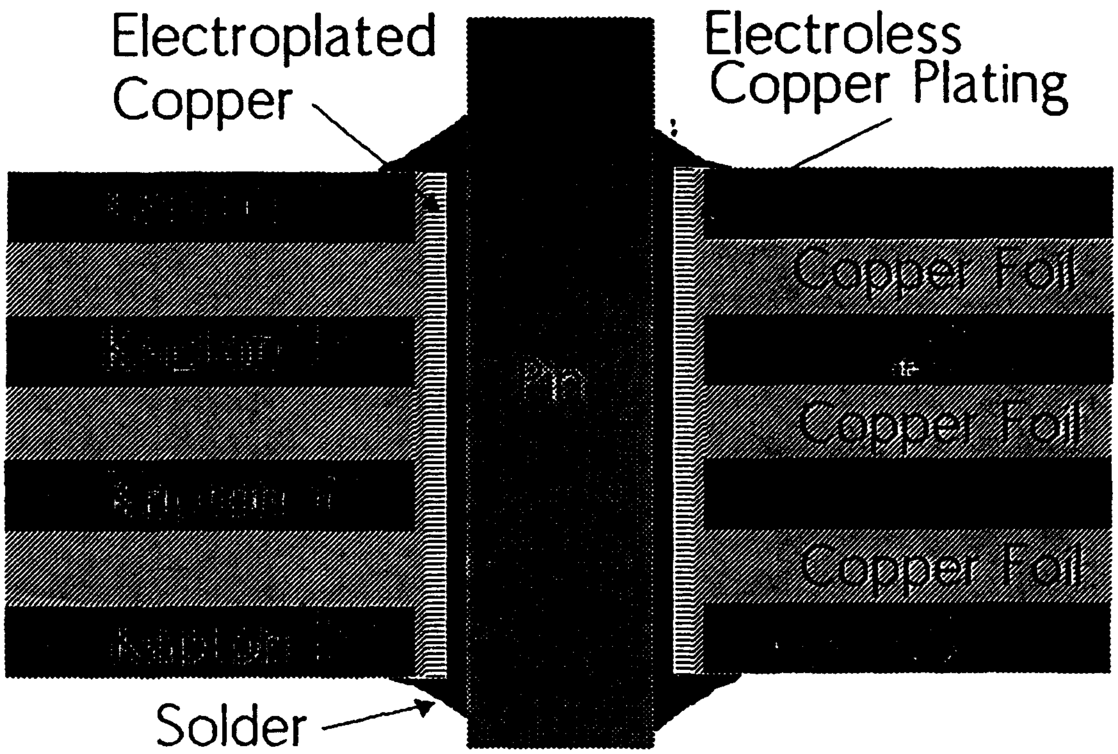

Figure 3. Detail of feedthrough hole in flexcable.

B. FLEXCABLE ANOMALIES

Anomalously high DC resistances were found in some flexcables. For example, in one cable configuration, two redundant pulse driver circuits make contact (upper right in Figure 2) to the inner, signal layer of the cable. A rough sketch illustrating the geometry of the driver pins is shown in Figure 4. The resistance between the primary and redundant brass driver pins, spaced 0.8 in. (2 cm) apart, should be about 2 mΩ. This value simply represents the resistance of the copper foil itself ($R = \rho L/A$, using the resistivity of bulk copper and with length, width, and thickness values of 2 cm, 0.5 cm, and 36 μm respectively). Resistances as high as 300 mΩ were measured in some cables. When feedthrough pins were metallographically cross sectioned for analysis, severe "etchback" of the foil was discovered. The cross section, shown in Figure 5, a composite picture derived from TRW scanning electron micrographs, represents a worst case (dimensions in inches). The copper foil had been thinned significantly in an acid etching step during manufacture. Subsequent plating operations left the void shown. However, even though considerable thinning of copper was observed, it is still difficult to reconcile the experimental observations with the highest of the measured resistances. The cross-sectional view of Figure 5 shows only a "slice" in a single plane through a pin and does not provide a complete determination of the foil connectivity all around the perimeter of the feedthrough. However, if we consider some of the dimensions of Figure 5 to be reasonably well defined, we can model the foil connectivity as indicated in Figure 6. For simplicity, we assume that the cross section of the foil providing the electrical continuity is rectangular rather than wedge shaped. We further assume that the conducting path from the foil to the post is constricted to a region about 0.001 in. (25 μm) long, 0.0002 in. (5 μm) high. Suppose now that the conducting path is not a 360° annulus but is limited to a single small filament. A resistance of 300 mΩ corresponds to a filament with an area ($= \rho L/R$) of only 1.4 μm^2 and a width (assuming a thickness of 5 μm) corresponding to only 0.28 μm. This width is certainly comparable to or smaller than the metal grain size and verges on being physically unreasonable. A 360° band of copper of length L and thickness t would have a resistance of only about 3×10^{-5} ohms.

Other explanations of the anomalous resistance are conceivable; e.g., the formation of a resistive interfacial layer between the pin and the foil. However, the cross-sectional analyses made by TRW do strongly suggest that the simplest explanation, a very substantial decrease in the conducting area around a throughhole, is very likely at least a part of the answer to the puzzle of the high resistances. The interpretation of the measured cable resistances is complicated by the fact that measurements are generally made with two feedthroughs in series. Nevertheless, it seemed potentially fruitful to consider further the implications of the existence of very constricted conducting current paths in the flexible cable similar to those depicted in the model of Figure 6.

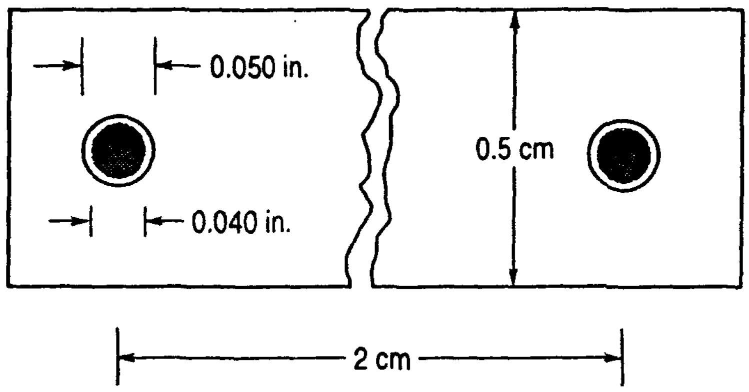

Figure 4. Sketch of driver pin configuration.

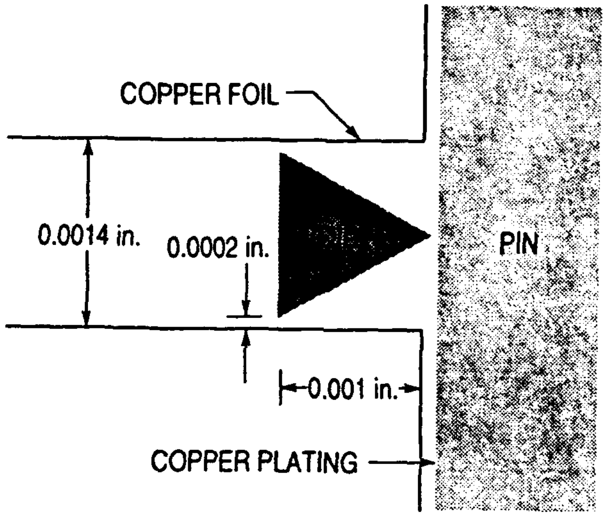

Figure 5. Feedthrough connection, with illustration of foil etchback.

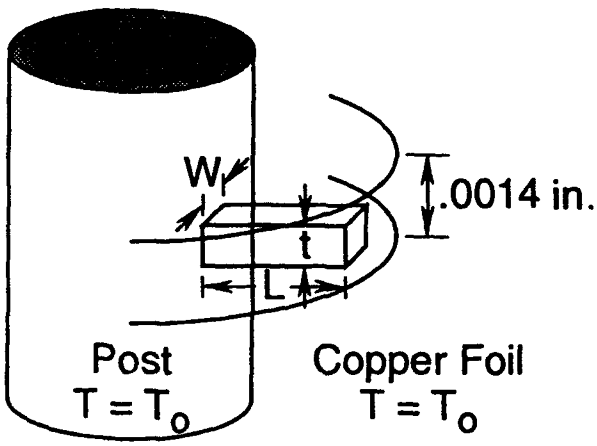

Figure 6. Model for feedthrough connectivity.

III. FLEXCABLE SCREENING: CONCEPT

In principle, "bad" cables should be detectable simply by measurement of the DC resistance of the traces. In practice, the essential difficulty is that the DC resistance contributed by defective regions can be small compared to that of the remainder of the foil trace metallization, even though the metallization in these regions is of sufficiently poor quality that cable life time could be seriously reduced. It is difficult to discriminate between the possibly small resistance of the degraded region and the much larger series resistance of the rest of the cable metallization. The work initiated at Aerospace, and completed at TRW and EMS, sought a method to selectively measure the resistances contributed by defective regions of metallization and a way to relate these measured resistances to the metallization quality and thus to cable reliability.

Nonlinearities in current-voltage characteristics are one phenomenon which has been used for the investigation of defects in passive components such as resistors, capacitors, and switch contacts. Such nonlinearities will result in the generation of harmonics of the driving signal. More recently, researchers have applied driving signals at two frequencies and have then looked for the sum and difference frequencies to study component defects.[1] A method for nonlinear resistance measurements using pulsed wave forms was described some years ago by workers at Bell Laboratories.[2,3] The pulse method has several advantages for flexcable investigations compared to more conventional systems based on sine wave excitation. These advantages include experimental simplicity and the possibility of measuring the thermal time constants of the components tested. The pulse method will be described, along with the initial laboratory experiments that validated the applicability of the technique to flexcables. Physical models for the origin of nonlinear resistance will then be discussed.

A. PULSE TECHNIQUES FOR THE CHARACTERIZATION OF RESISTANCE NONLINEARITIES.

A schematic diagram of the pulse apparatus is shown in Figure 7. Current pulses are applied to a resistor by a constant current source, i.e., the resistance of the source is large compared to that of the device under test. The current pulse train has a repetition time τ and is applied through a large coupling capacitor, C. The capacitor has low leakage and a capacitance high enough that the pulse wave train is passed without any change in shape. The applied current waveform is shown in the upper left inset of Figure 7. The current pulse amplitude is I, the repetition time is t and the duty cycle is F. The wave form is assumed to be referenced to ground. The key to the pulse technique is that the series blocking capacitor cannot pass the DC level (i.e., the average value) associated with the generated waveform, i.e., no net charge can flow through the capacitor. Current flows first in one direction and then must change sign. The wave form thus applied to the device under test (i.e., the resistor of interest) must have an average value of zero, i.e., the capacitor imposes the requirement that

$$I_1 F = I_2 (1 - F) \quad (1)$$

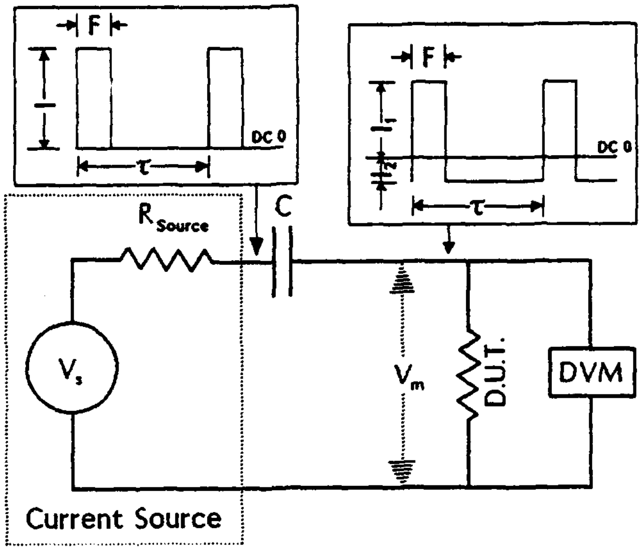

Figure 7. Nonlinear resistance measurements.

where I_1 is the peak positive current amplitude (referenced to ground), I_2 (taken to be a positive quantity) is the peak amplitude in the negative direction, and $I = I_1 + I_2$. The average (DC) voltage measured across the device under test is just

$$V_{dc} = R(I_1)FI_1 - R(I_2)I_2(1-F) \tag{2}$$

If the device under test is linear, then $R \neq R(I)$ and V_{dc} is identically equal to zero because of the requirement of Eq. (1). In the flexcable problem, we really are interested in resistors which exhibit nonlinear characteristics and the DC voltage can be nonzero. "Nonlinear" behavior means that the resistance is not constant with respect to current but is in general expressible as a power series expansion in I, i.e.,

$$R(I) = R_0 + AI + BI^2 + CI^3 + \ldots \tag{3}$$

Resistor nonlinearity should be symmetric in powers of I. This is certainly true for the thermally induced nonlinearities that we shall be dealing with shortly since power dissipation is independent of the direction of current flow. Only even terms will occur in the expansion, and the resistance is represented to lowest order in I by the expression

$$R(I) = R_0\left(1 + \lambda I^2\right) \tag{4}$$

Substituting Eq. (4) in Eq. (2) one finds after a bit of algebra that

$$V_{dc} = \lambda R_0 I^3 F(1-F)(1-2F) \tag{5}$$

Equation (5), among other things, satisfies the physically essential requirements that the DC voltage must be zero if F = 0 (no applied current), if F = 1 (applied DC current) or if F = 1/2 (a symmetrical waveform). The maximum value of the DC voltage, V_{dc}, is obtained by maximizing Eq. (5) with respect to F, which we are at liberty to do in our experiments. The maximum value of V_{dc} occurs when $F = 1/2 \pm 1/(12)^{1/2}$, i.e., for F = 0.21 or F = 0.79. Substituting F = 0.21 in Eq. (5), we obtain

$$V_m = 0.096\,\lambda R_0 I^3 \tag{6}$$

The essential connection between nonlinearities in resistance and cable reliability is through the observation that the temperature dependence of the resistance of a metal is represented as

$$R(T) = R_0\left(1+\alpha\left(T-T_0\right)\right) \tag{7}$$

By combining Eq. (7) with Eq. (4), the nonlinear voltage parameter, λ, can be related to the parameters of the flexcable and to heating in the flexcable.

B. CABLE HEATING

Metallurgical cross sectioning showed definitely that there are marginal cables with thinned metallization. We make the assumption that measured cable resistance anomalies are simply caused by a decrease in the cross section of the copper. As yet no model for the high measured resistances has been proposed that is wholly satisfactory and physically reasonable. The reduced area model does imply that very small, possibly physically implausible areas might be involved. Nevertheless, some of the logical implications of the reduced area model can be examined. A more detailed consideration of a simple reduced area model could provide insight into the heating to be expected in flexible cables under pulse current conditions and provide some guidance in the determination of parameters relevant to cable testing.

The remaining copper paths in marginal cables might conceivably be broken by mechanical stress, by external thermal stress, or by thermal stress generated by internal ohmic losses. The conducting filaments could simply melt. All such mechanisms could lead to high resistances or to completely open cables. Would a significant temperature increase be expected in a flexcable subjected to current pulses? We again refer to the model of Figure 6. The copper connectivity at a feedthrough is provided by a single rectangular filament of length L, width w, and thickness t. The ends of the filament are maintained at T_0 by the effectively massive heat sinks formed by the remainder of the foil layer and by the central metal post. We assume the temperature in the filament is adequately described as a problem in one-dimensional heat flow. If the heat generated by ohmic loss in the filament is dissipated entirely by conduction out the ends, then the maximum temperature rise with an 8 A current pulse may be calculated using Eq. (A7) and is about 40°C. This result assumes that the thermal time constant is small compared to the width of the current pulses. The thermal time constant can also be calculated [from Eq. (A11)] and is only 140 nsec. Details of these calculations will be found in the Appendix.

If heat is lost by conduction not out the ends but out the sides of the filament through the Kapton insulation (which is about 0.001 in. thick [d_k], thermal conductivity 1.7 x 10^{-3} watts/cm/C [κ_k]) to the surrounding copper foils at ambient temperature, the temperature rise can also be calculated by equating the heat dissipated in the filament by ohmic losses to the heat flow through the insulation. The result is

$$T - T_0 = \frac{1}{w^2 tL} \frac{d_k}{2\kappa_k} \rho_0 I^2 = \frac{1}{wL} \frac{d_k}{2\kappa_k} R_0 I^2 \qquad (8)$$

Inserting the appropriate numerical values yields an astronomically large temperature rise for our model 0.3 ohm filament.

In view of the gross approximations involved, these calculations mainly serve to show that the occurrence of significant heating in flexcables is indeed plausible, although the magnitude of the effect is not certain.

C. LABORATORY VALIDATION

1. Apparatus

The experimental configuration shown in Figure 7 is fairly easy to implement in practice, although some thought had to be given to the current source used because of the relatively high peak pulse amplitudes (a few amperes) required for flexcable testing. We employed a high current operational amplifier* and a series resistor as a current source. A Keithly Model 177 digital multimeter served to measure V_{dc}. A Wavetek function generator supplied a pulse train with variable frequency and duty cycle. Peak-to-peak pulse amplitude was measured using a Hitachi V060 oscilloscope.

DC cable resistances were measured using a small bench top power supply as a current source and digital mulitmeters to measure the current through and the voltage across cable traces.

2. Initial Experimental Results

a. Flexcables

A necessary step in the development of the nonlinear resistance technique was a demonstration of its applicability to flexcables. It was by no means initially obvious that the application of the method would be met with any success at all. A flexcable, S/N 1080, which exhibited excessively high DC resistance in some traces, was provided for the Aerospace investigation. The appearance of this cable is as shown in Figure 1. The primary and redundant driver pins, spaced 0.8 in. apart as described in Section II, were usually used in our measurements. There are some experimental complications. DC resistance values between these pins on each trace were supplied by the contractor and were remeasured several times at Aerospace in the course of the investigation. The resistance values on some traces, especially those initially indicated as having an anomalously high resistance, were not constant. The only way to make reliable connections to the feedthrough pins was to insert and solder in place short (1 in.) lengths of tinned copper wire which could be easily grasped by clip leads. EMS, Inc. also had to use soldered connections in their investigation of cables from stores (this

* Type PA05, Apex Microdevices, Tucson, AZ

fact will later be significant). Our measurements of the primary to redundant driver pin resistances in cable S/N 1080 ranged from about 5 mΩ to essentially an open circuit.

We were immediately able to verify that the current-voltage response was nonlinear, with an I^3 behavior of the measured DC voltage. In Figure 8, the circles represent experimental data points while the straight line is simply a plot of an I^3 relationship fit through the data at 1 ampere. The data was obtained with a pulse repetition frequency of 2 KHz. The magnitude of V_m can be used to estimate the corresponding temperature rise. Comparison of Eqs. (4) and (7), combined with Eq. (6) leads to the relation

$$\Delta T = \frac{10V_m}{\alpha R_0 I} \tag{9}$$

Substituting numbers from the data illustrated in Figure 8 yields a temperature increase of about 30°C for a pulse amplitude of 2.5 A. Again, although rather gross approximations are involved, the result is at least consistent with resistive heating thermal models. In general, the agreement between theory and experiment is remarkable.

Further confirmation of the validity of Eq. (5) is provided by a plot of V_{dc} vs pulse duty factor, again at a constant 2 KHz pulse frequency (Figure 9). V_{dc} reaches its maximum value at 21% duty cycle, goes to zero at duty cycles of 0% and 50%, and closely follows the theoretical F(1-F)(1-2F) dependence.

As mentioned, one advantage that the pulse method enjoys over other methods for the investigation of nonlinearities *is that the thermal time constant* of the resistor under test can be determined. The thermal time constant was an important question in the flexcable investigation because knowledge of this parameter determines whether life testing can be accelerated. Equation 6 is valid only if the thermal time constant of the resistor under test is short compared to the width of the applied current pulses. During the positive-going portion of the applied AC-coupled pulse train, the temperature is assumed to rise very quickly and just as quickly fall to reequilibrate at a new temperature as the current changes sign and magnitude. If this condition is not met, the test resistor temperature tends to some average value over the entire pulse cycle and the magnitude of V_{dc} decreases. The time constant can be inferred from a plot of V_{dc} vs the frequency of the applied pulse train, as shown in Figure 10. The duty cycle was set to a constant 21% while the pulse amplitude was set to 1.5 A to obtain the data. The thermal time constant for the data illustrated is on the order of 50 μsec. This value, although typical of flexcable traces and unambiguously determined by experiment, is difficult to reconcile with physical models of the nonlinear resistance effect and seems too long based on the estimates made in Section IIIB.

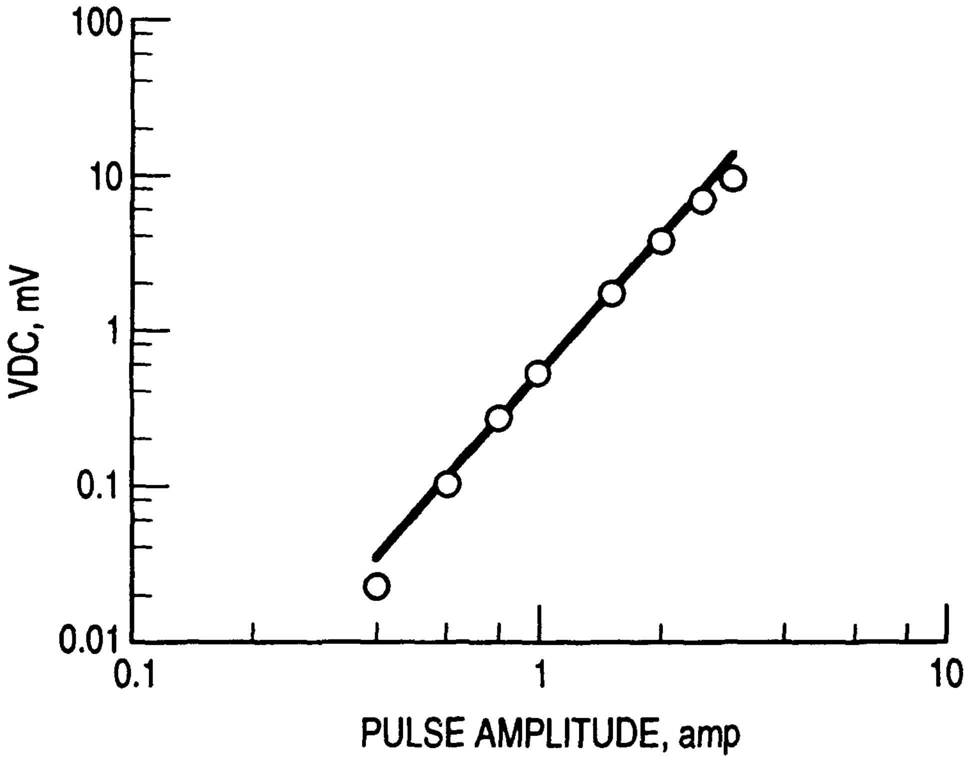

Figure 8. Current/voltage characteristic, flexcable S/N 1080, trace A-B.

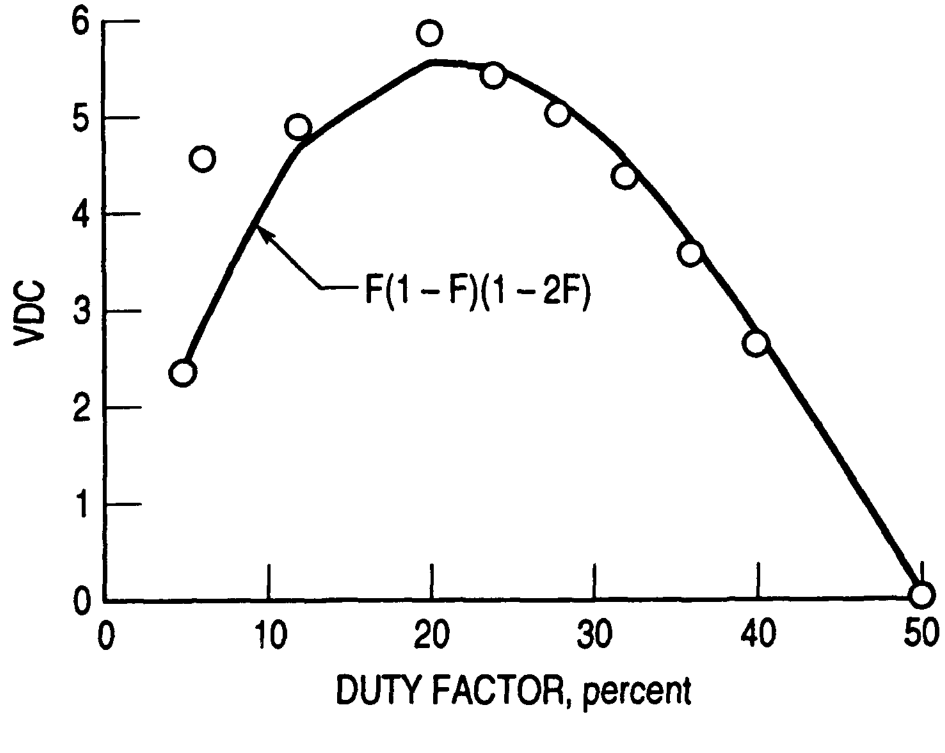

Figure 9. V_{dc} vs duty cycle. Cable S/N 1080, Trace M-N.

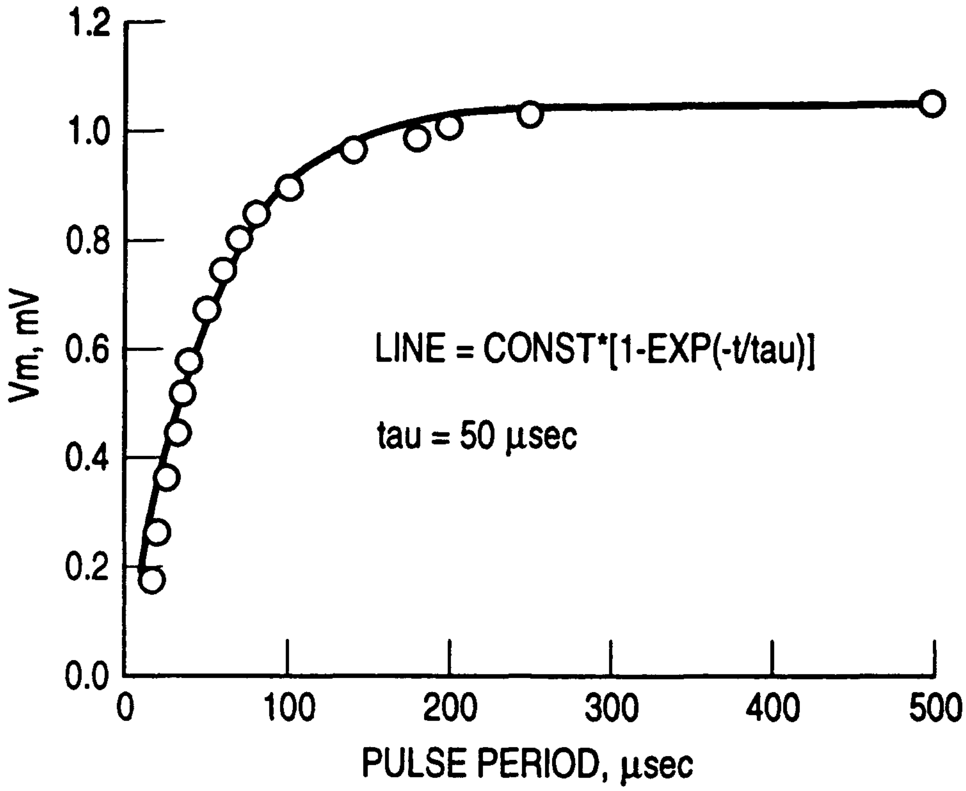

Figure 10. Determination of flexcable time constant through variation of pulse frequency. Cable S/N 1080, Trace A-B.

b. Validity Checks

After verifying that nonlinear resistance was observable in flexcables, the method was applied to other systems as a sort of "sanity check". These results will only be mentioned briefly here. They are not of critical importance to the present investigation of flexcables although the work could well be used as a foundation for future development and extension of the technique.

The meltable link in a 1/32 ampere, type 3AG fuse is a platinum wire about 5.4 μm in diameter and 3.65 mm long. This fusible link is supported by relatively massive copper lead wires. The fuse seemed to offer a good model system. A nonlinear voltage proportional to I^3 was indeed found. The measured thermal time constant was 24 msec. The calculated thermal time constant (see Appendix) was 13 msec. Given the crudeness of the assumptions involved, the agreement between theory and experiment is quite acceptable.

Copper traces of varying lengths and widths were deposited on oxidized silicon substrates in an effort to construct a model system more closely approximating a flexcable. These traces all displayed a nonlinear current-voltage characteristic with an exact (to within the accuracy of measurement) I^3 dependence. The thermal time constants were measured for traces with varying lengths and widths. Cooling was assumed to be primarily by conduction through the oxide to the silicon substrate. The trends in the data were generally as expected but further work is needed.

IV. FLEXCABLE SCREENING: APPLICATION

Work at Aerospace led the antenna contractor to undertake their own flexcable investigation with the ultimate goal of screening the installed cables.

A. APPARATUS

EMS initially concluded that the sensitivity obtained using a digital voltmeter with an integrating filter was not adequate for flexcable screening. They were able to greatly enhance the sensitivity of their apparatus by incorporating a low noise operational amplifier* ahead of the digital voltmeter. The amplifier stage is operated in the usual inverting configuration with a gain of 1000. They can detect any signals above their "noise floor," which is about 100 nV. EMS also carried out V_{dc} measurements on cables connected in series with other components (such as ferrite inductors) to simulate the environment of the installed flight hardware. These tests were successful and indicated that the method could be applied *in situ* to the antenna assemblies. A great advantage of the pulse technique over DC resistance methods is that the effect of any intervening conductor between the feedthroughs of interest and the test apparatus should not affect the measurement. Extra test lead length might contribute noise, but as long as the conductors do not get hot they should not affect V_{dc}.

B. CONTRACTOR RESULTS

EMS screened the 800 Protosystems flexcables in their stores using the nonlinear resistance method. They originally found only two cables that exhibited a measurable effect. Five additional cables were subsequently discovered using the improved apparatus with the low noise amplifier. One of these cables (S/N 722), had a nonlinear voltage reading of 3.3 μV (measured at 8 A peak-to-peak current pulse amplitude) in a signal trace path through two feedthroughs. This cable was sent to TRW for cross-sectional analysis. TRW developed a semiquantitative method for evaluating the connectivity at plated through holes. Metallographic cross-sections are taken through seven planes in the feedthrough as shown in Figure 11. Each plane provides a view of the metallization connectivity at two sides of the feedthrough hole, for a total of 14 data points. Connectivity was rated as "1" (some bridging copper evident) or "0" (an apparent open circuit) at each of the 14 locations. The "percent connectivity" was taken to be the number of points with any connectivity, divided by 14. Cable S/N 722 had 36% connectivity at one feedthrough and 100% at the other feedthrough. Aerospace and the contractors agreed, based on analyses of mechanical stress, that cables with feedthroughs showing a connectivity less than 50% would be suspect, while greater than 50% connectivity would be acceptable. The results on cable S/N 722 were encouraging. The 3.3 μV signal was easily measurable, yet the connectivity of one of the feedthroughs was only 36%. These results indicated that screening of flexcables was feasible.

A test plan for the remaining cables containing traces with anomalous resistance was therefore proposed and accepted by Lockheed (the Milstar prime contractor), TRW, EMS, and Aerospace. The remaining seven nonlinear cables discovered in stores, along with the original cable S/N 1080 used in preliminary measurements at Aerospace, were to be subjected to a number of current pulses sufficient to simulate the stresses expected over the duration of the mission. Calculations indicated that substantial acceleration could be obtained by increasing the pulse amplitude. The cables would also be temperature cycled although not, for reasons of experimental convenience, at the same time the current pulses were being applied. After testing, the nonlinear voltage characteristics would again be

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* Type OPA27, made by Burr-Brown, Inc., Phoenix, AZ.

measured and the feedthroughs in the anomalous traces of the cables would be cross sectioned using the seven-plane method to evaluate their connectivity. The data, in addition to establishing more firmly the relation between nonlinear voltage and copper connectivity, would also indicate whether a cable with a particular connectivity would survive the stresses expected in the course of the mission. This information would then be used to formulate a "fly - no fly" criterion for the cables to be screened *in situ* in the assembled antenna.

One other requirement was added to the plan. *In situ* testing could not be completely "non-invasive". Cables would have to be unsoldered at one (reasonably accessible) end, tested, then resoldered. Given the condition of the metallization observed in some cables, the soldering operation could prove quite stressful. Therefore, the pins in the test cables were unsoldered, resoldered, and the cables then remeasured before the pulse and temperature cycle testing to assess the effect of soldering. The results are shown in Table 1. The flexcable anomalous trace resistances were not stable through the soldering operation. This result implies that the copper connectivity at the feedthrough connectors is sufficiently poor that the cables simply can not be relied upon to perform successfully. *In situ* testing and resoldering of the flexcables would itself very likely cause degradation and there is no way to ensure after resoldering and reassembly that the resistance of flexcable traces had not changed during the screening test.

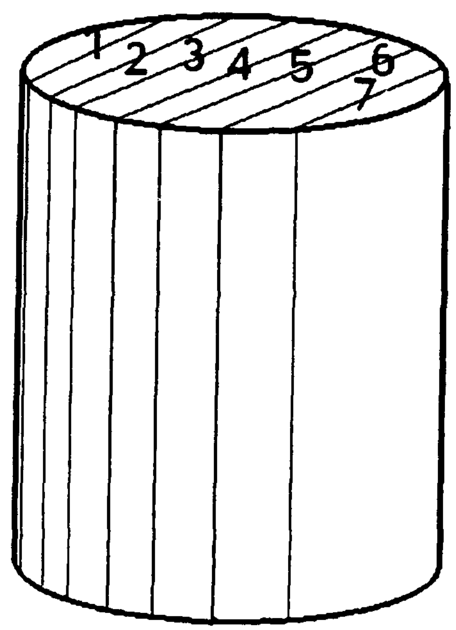

Figure 11. Feedthrough cross sectioning for metallographic analysis.

Table 1. Flexcable Nonlinear Voltage Measurements

Cable S/N (Trace Number)	Initial V_{dc} (μV)	Final V_{dc} (μV)
004	17	110
005 (Trace 1)	120	3.6 Ohms!
005 (Trace 2)	40	132
029 (Trace 1)	32	55
029 (Trace 2)	50	47
029 (Trace 6)	39	0
029	16	0
700	6	0
709	26	Open
718	3	Open
729	3	7
1080	35	35

V. DISCUSSION

The potential utility of the pulse nonlinear resistance method for the screening of flexible cables has been demonstrated. The manifestation of a nonlinear behavior in these cables is an established fact. The details of the physical mechanism responsible for the nonlinearity have not yet been unambiguously established. The origin of the effect almost certainly lies in localized resistive heating in feedthrough connectors with very restricted copper cross sections. The observation of an essentially perfect cubic relationship between the amplitude of the current pulses and the measured V_{dc} is convincing evidence in support of the localized heating model. However, understanding of electrical conductivity in imperfect conductors, such as those as represented by the flexcables, is still incomplete and would be a potentially fruitful area for investigation and practical exploitation. It is interesting to note that the apparently most relevant published work uncovered to date has actually been concerned with electrical conductivity at relay contacts.[4,5] This work does not appear to have been extended much beyond applications to relay contacts and could profitably be broadened. A contact between two metals not intimately joined together can be represented as in Figure 12. There are still some regions of intimate metal-metal contact, regions where metals are separated by a gap, and regions where the space between the metals is filled by oxides or organic contaminants. Figure 12, which was taken from Ref. 5, should also be broadly representative of the situation in degraded flexcables. Imperfect metal-metal contacts will give rise to various types of nonlinearities that can be investigated by the pulse method or other techniques for current-voltage characterization.

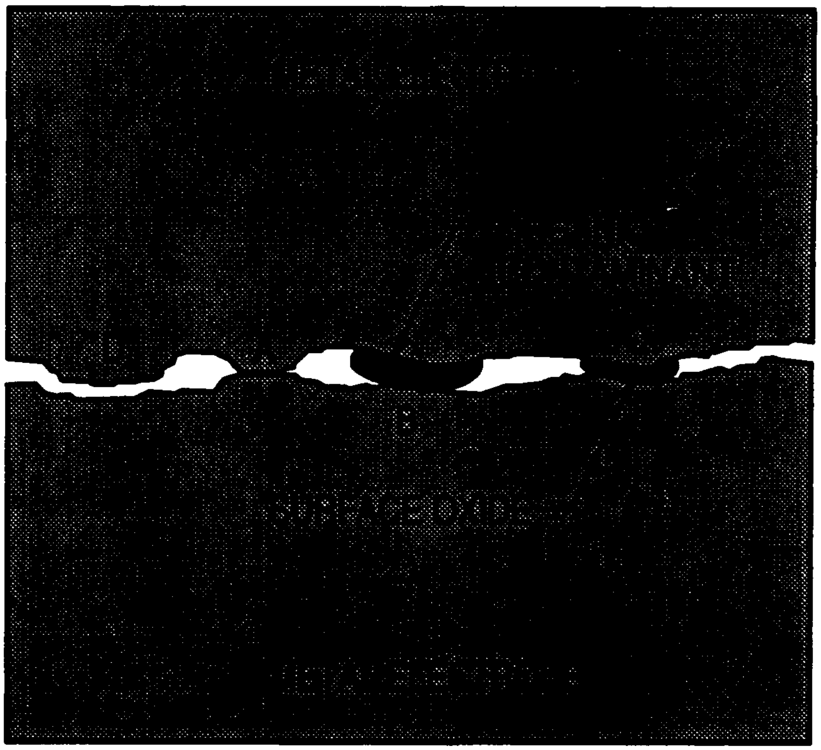

Figure 12. Imperfect electrode contact. (A) "good" metal-metal region. (B) metal-insulator-metal region. (C) metal-oxide-metal region. (D) metal-gap-metal region.

A number of intriguing possibilities for the investigation of nonlinear effects in small conductors will be afforded by the acquisition of a focused ion beam (FIB) system in the Electronics Technology Center. Work at Lockheed has already employed FIB to produce very small (200 Å) conducting links in an investigation of programmable random access memories. It should be possible to monitor nonlinear effects even while conductor dimensions are reduced by ion milling.

VI. SUMMARY AND CONCLUSIONS

The nonlinear resistance technique proved useful for the screening of flexcables in large quantities and under more or less "field conditions". No other method seemed suitable for use as a screen for the installed cables in this particular Milstar application. After the development of apparatus with improved sensitivity, cables in the contractor's stores were first screened in order to develop baseline data correlating measured values of the nonlinear voltage to the degree of mechanical connectivity in feedthrough connections. The sensitivity of the test procedure was sufficient to find an additional eight defective cables out of 800 tested. The nonlinear resistance method worked! However, nonlinear voltages and the DC resistances of these cables were not stable when the feedthrough connections were resoldered. These observations were sufficiently alarming that replacement of cables in the flight hardware was deemed necessary even without testing of the installed cables.

The work carried out to date strongly suggests that nonlinear resistance effects could be exploited for the testing and screening of components of various types, including but certainly not limited to flexible cable assemblies. The technique offers a number of potential advantages including: greater sensitivity than DC resistance methods; its generally nondestructive nature; and the possibility of *in situ* component evaluation. As the method is developed further, the MIL STDs applicable to flexible cables and other types of components might well be revised to incorporate nonlinear resistance measurements. Additional work should be undertaken to determine whether the nonlinear resistance method can be routinely applied in the testing of spacecraft components.

REFERENCES

1. M. Kanno and I. Minowa, "Application of Nonlinearity Measuring Method Using Two Frequencies to Electrical Components", *IEEE Trans. IM IM-4*, p. 590-593 (1985).

2. A. T. English, G. L. Miller, D. A. H. Robinson, L. V. Dodd, and T. Chynoweth, "Pulse Nonlinearity Measurements on Thin Conducting Films", *J. Appl. Phys. 49*, p. 717-722 (1978).

3. E. Kinsbron, C. M. Melliar-Smith, A. T. English, and T. Chynoweth, "Failure of Small Thin Film Conductors Due to High Current Pulse Densities", *Proc. IEEE 1978 Rel. Phys. Symp.*, p. 248-254 (1978).

4. I. Minowa and M. Iwamoto, "Nonlinear Characteristics of Electrical Insulating Films with nm Thickness Sandwich between Au-Au Contact", *Proc. 36th IEEE Holm Conference on Electrical Contacts*, p. 248-255, Montreal, Quebec, Canada (August 20-24, 1990).

5. C. G. Karagiannopoulos, P. D. Bourkas, C. T. Dervos, and C. A. Kagarakis, "Physical Interpretations Concerning Non-Linear Conductivity Across No-Load Switching Contacts", Proc. 36th IEEE Holm Conference on Electrical Contacts, p. 611-618, Montreal, Quebec, Canada (August 20-24, 1990).

APPENDIX

Flexcable internal heating has been estimated using the crude model shown in Figure 6 and with the introduction of several simplifying assumptions. We assume that a significant fraction of the measured DC resistance of a conducting path on a flexcable originates in a small "filament". The filament carries the total current through the cable. The filament, as indicated in Figure 6, is taken to have a uniform cross section of area A and a length L and is constrained to a temperature T_0 by the relatively massive amounts of copper at each end. It is further assumed that the temperature distribution in the filament, which is internally heated by ohmic loss, is adequately represented as a problem in one-dimensional heat flow. Losses due to conduction of heat away from the sides of the filament and losses due to radiation are neglected. These assumptions, while rather sweeping, do at least render the problem more tractable.

The basic definition of heat flow is:

$$F = -\kappa \nabla T \tag{A1}$$

where F is the thermal flux and κ is the thermal conductivity. The continuity equation is:

$$-\nabla \cdot F + \dot{Q} = C_v \frac{\partial T}{\partial t} \tag{A2}$$

where

$$\dot{Q} = \rho \cdot J^2 \tag{A3}$$

is the resistive heating/unit volume. J is the current density(i.e., the current per unit area).

The temperature in a filament of length "L" and area "A" in the steady state, constrained to a constant temperature T_0 at the ends (i.e., we assume the filament shorts between massive heat sinks), is found to be

$$T(x) = T_0 + \frac{1}{\alpha}\left[\frac{cos(\gamma x)}{cos(\gamma L/2)} - 1\right] \tag{A4}$$

where

$$\gamma^2 = \frac{J^2 \rho_0 \alpha}{\kappa} \tag{A5}$$

κ is the thermal conductivity and J is the current density. The temperature coefficient of resistance of copper, α, is explicitly included in this result, i.e., it is assumed that the resistance varies with temperature as

$$\rho = \rho_0 \left(1 + \alpha(T - T_0)\right) \tag{A6}$$

The maximum temperature is at the center of the filament (x = 0 in the coordinate system chosen) and is given by

$$T_{max} = T_0 + \frac{1}{\alpha}\left[\frac{1}{cos(\gamma L/2)} - 1\right] \tag{A7}$$

The filament melts (and the cable may fail open) when

$$cos(\gamma L/2) = \frac{1}{1 + \alpha(T_{melt} - T_0)} \tag{A8}$$

If the temperature coefficient of resistance is not included, the solution of Eq. (1) reduces to a parabolic temperature distribution.

For circuits in which operation is not continuous but pulsed, the thermal time constant of a filament is of interest in estimating whether filaments might be blown open. The calculation of the thermal time constant is therefore included here for completeness. A complete solution of the time-dependent heat flow equation for the case in which the wire is being heated by a current is

$$T(x,t) = T_0 + \frac{\rho J^2}{2\kappa}\left[\frac{L^2}{4} - x^2\right] + \sum_{n=1}^{\infty} A_n \, cos(\alpha_n x)\, exp - \left[\alpha_n{}^2 \frac{\kappa}{c_v} t\right] \tag{A9}$$

For a filament subjected to a current pulse at time t = 0, the coefficients A_n are selected so that the Fourier series expansion term cancels the second term at time t = 0, assuming that the wire is initially at a uniform temperature T_0. The $\alpha_v = 2\pi n/L$, and one finds that the coefficients A_n are

$$A_n = -\frac{\rho J^2 L^2}{\kappa} \frac{1}{\pi^2 n^2} \quad (n\ odd) \tag{A10}$$

The solution for the case of a filament with some particular initial temperature is essentially the same. One just has to pick the coefficients to match the initial temperature distribution, which then decays to a uniform temperature. One can construct the solution for the general case of a current pulse of duration comparable to the thermal time constant.

The essential point is that the transient terms decay with time constants given by

$$\tau = \frac{L^2}{4\pi^2 n^2} \frac{1}{\frac{\kappa}{c_v}} \qquad \text{(A11)}$$

with the longest time for $n = 1$. The quantity κ / c_v is known as the thermal diffusivity.

TECHNOLOGY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Technology Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual Technology Centers:

Electronics Technology Center: Microelectronics, solid-state device physics, VLSI reliability, compound semiconductors, radiation hardening, data storage technologies, infrared detector devices and testing; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; cw and pulsed chemical laser development, optical resonators, beam control, atmospheric propagation, and laser effects and countermeasures; atomic frequency standards, applied laser spectroscopy, laser chemistry, laser optoelectronics, phase conjugation and coherent imaging, solar cell physics, battery electrochemistry, battery testing and evaluation.

Mechanics and Materials Technology Center: Evaluation and characterization of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; development and analysis of thin films and deposition techniques; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; development and evaluation of hardened components; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion; spacecraft structural mechanics, spacecraft survivability and vulnerability assessment; contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; lubrication and surface phenomena.

Space and Environment Technology Center: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation; propellant chemistry, chemical dynamics, environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, and sensor out-of-field-of-view rejection.