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Theoretical models of Kapton heating in solar array geometries

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ABSTRACT

In an effort to understand pyrolysis of Kapton in solar arrays, a computational heat transfer program was developed. This model allows for the different materials and widely divergent length scales of the problem. The present status of the calculation indicates that thin copper traces surrounded by Kapton and carrying large currents can show large temperature increases, but the other configurations seen on solar arrays have adequate heat sinks to prevent substantial heating of the Kapton. Electron currents from the ambient plasma can also contribute to heating of thin traces. Since Kapton is stable at temperatures as high as 600 Celsius, this indicates that it should be suitable for solar array applications. There are indications that the adhesive used in solar arrays may be a strong contributor to the pyrolysis problem seen in solar array vacuum chamber tests.

INTRODUCTION

During plasma compatibility tests of the SSF solar array blanket, pyrolysis of Kapton® (registered trademark of E.I. du Pont de Nemours & Co., Inc.) was seen.[1] While performing a dark test, the experimenters biased the array to a positive voltage, and read the current drawn from the ambient plasma. At +450 volts, a large spike was seen in the current. When the solar panels were removed from the test tank, a 1/8 inch hole was seen to have enlarged to about 1/2 inch diameter, with black char marks on the Kapton surrounding the hole.

Kapton was developed by du Pont in the early 1950's, and commercialized in 1966. It has been used extensively in the aerospace industry for 25 years with few problems. Various laboratory tests indicate that it does not pyrolyze until the temperature reaches at least 500° C.[2,3]

The objective of this paper is to determine possible causes of the pyrolysis, and determine the conditions under which they could be repeated. In addition, questions were raised about possible concerns when Kapton was used in the space environment. Under what conditions would Kapton pyrolyze, and would those conditions happen often?

METHOD OF CALCULATION

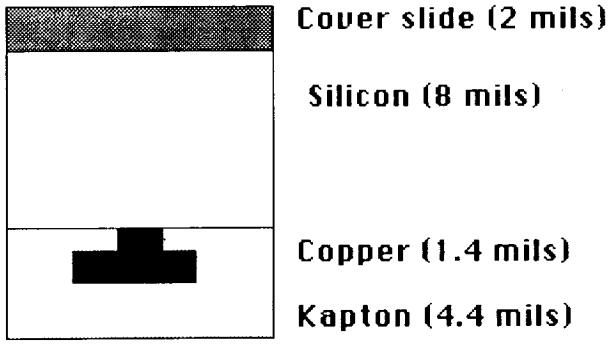

Figure 1 - Cross Section of Solar Cell

To study this problem, a computational heat transfer computer program was developed. A new program was needed because of the unique geometry of this problem. The solar cells are very thin, as shown in Figure 1. The entire thickness is about 15 mils, while the hole that was examined was 1/8 inch in diameter (125 mils). This disparity in scales does not allow the direction perpendicular to the surface to be treated in the same way as the directions parallel to the surface.

A schematic of the calculation geometry is shown in Figure 2. Both the hole, and the paths for heat gains and losses are shown. For most of the calculations, it was assumed that incident radiation was coming in

from a 300 K source. In addition, resistive heating was ignored for most of the calculations, since the system modeled was a dark solar panel, that is, no current was present.

Thus, the heat sources and paths are as follows:

1. Energy transfer from incoming electron, set equal to current times bias voltage.
2. Conduction of heat through copper, kapton, and silicon.
3. Radiation heat gain from external source at 300 K.
4. Radiation heat loss from surfaces, equal to $\epsilon\sigma T^4$, where ϵ is the emissivity , σ is the Stefan-Boltzmann constant, and T is the absolute temperature at the surface.
5. Internal Joule heating of copper from I^2R.

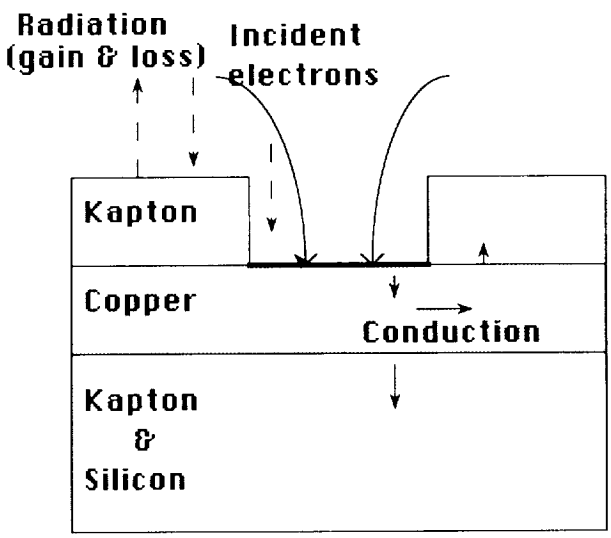

Figure 2 - Heat pathways

Different materials were included in this calculation, as listed in Table 1. The adhesives were treated as Kapton, since their thermal properties are similar, and could not be identified until late in the calculation.

Parameter \ Material	Kapton	Copper	Silicon
Density (g/cm^3)	1.42	8.96	2.33
Specific Heat (J/g K)	1.09	.385	.702
Thermal Conductivity (W/cm K)	.00155	4.01	1.49
Resistivity ($\mu\Omega$ cm)	10^{18}	1.69×10^{-8}	640.
Emissivity	.7	.65 (oxidized)	not used

The fundamental equation for heat transfer is

$$\rho c \frac{\partial T}{\partial t} - \kappa \nabla^2 T + \dot{Q} \qquad (1)$$

where ρ is the density, c is the heat capacity per unit mass, and κ is the thermal conductivity. Writing $\alpha = \kappa / (\rho\, c)$, the equations can be re-written as

$$\frac{\partial T}{\partial t} - \alpha \nabla^2 T + \frac{\dot{Q}}{\rho c} \qquad (2)$$

For this calculation, a finite difference approach was chosen. Boundaries between difference materials were treated with a control volume approach. That is, the heat flowing into and out or a node from each direction would change the temperature of that node as if the node had the average properties of the materials around it.

In finite difference calculations, the time step is limited by stability requirements. If the calculation is done explicitly, it is necessary to maintain a ratio

$\frac{\kappa \Delta t}{\rho c (\Delta x)^2} < \frac{1}{2}$ where Δt is the time step, and Δx is the distance scale. However, if the temperature at the succeeding time step depends implicitly on the surrounding temperatures, this restriction does not hold. Implicit calculations in one dimension are straightforward, but three dimensional calculations are difficult. For this reason, the calculation was done implicitly only in the z direction (i.e. perpendicular to

the surface of the Kapton).

For an explicit calculation, the temperature at time $n+1$ is simply

$$T_{i,j,k}^{n+1} = T_{i,j,k}^{n} + \frac{\alpha_x \Delta t}{(\Delta x)^2}(T_{i+1,j,k}^{n} - 2T_{i,j,k}^{n} + T_{i-1,j,k}^{n}) + \frac{\alpha_y \Delta t}{(\Delta y)^2}(T_{i,j+1,k}^{n} - 2T_{i,j,k}^{n} + T_{i,j-1,k}^{n}) + \frac{\alpha_z \Delta t}{(\Delta z)^2}(T_{i,j,k+1}^{n} - 2T_{i,j,k}^{n} + T_{i,j,k-1}^{n}) + \frac{\dot{Q}}{\rho c} \quad (3)$$

where $\alpha_i = \kappa_i/(\rho c)$, i=x,y,z. If we do an implicit calculation in the z direction, the formula becomes

$$T_{i,j,k}^{n+1} = T_{i,j,k}^{n} + \frac{\alpha_x \Delta t}{(\Delta x)^2}(T_{i+1,j,k}^{n} - 2T_{i,j,k}^{n} + T_{i-1,j,k}^{n}) + \frac{\alpha_y \Delta t}{(\Delta y)^2}(T_{i,j+1,k}^{n} - 2T_{i,j,k}^{n} + T_{i,j-1,k}^{n}) + \frac{\alpha_z \Delta t}{(\Delta z)^2}(T_{i,j,k+1}^{n+1} - 2T_{i,j,k}^{n+1} + T_{i,j,k-1}^{n+1}) + \frac{\dot{Q}}{\rho c} \quad (4)$$

Separating temperatures at time n from time $n+1$, we get

$$-d_z T_{i,j,k+1}^{n+1} + (1+d_z) T_{i,j,k}^{n+1} - d_z T_{i,j,k-1}^{n+1} = T_{i,j,k}^{n} + \frac{\dot{Q}}{\rho c} + d_x(T_{i+1,j,k}^{n} - 2T_{i,j,k}^{n} + T_{i-1,j,k}^{n}) + d_y(T_{i,j+1,k}^{n} - 2T_{i,j,k}^{n} + T_{i,j-1,k}^{n}) \quad (5)$$

where $d_i = \frac{\alpha_i \Delta t}{(\Delta i)^2}$ $i=x,y,z$. Von Neumann stability analysis requires that $d_x < \frac{1}{2}$, $d_y < \frac{1}{2}$. There is no restriction on d_z.

Since d_i has the spatial increment in the denominator, it is very useful to not restrict d_z. For these calculations, a $\Delta t = .0001$ seconds was used. This keeps both d_x and d_y within the stability requirements.

The boundaries between different substances were treated with a control-volume approach. That is, it was assumed that heat was transferred between nodes using an average of the transport properties of the materials involved. That is, the finite difference version of Eqn 1 becomes

$$(\rho c)_{av} \frac{(T_0^{n+1} - T_0^{n})}{\Delta t} = \dot{Q} + \left[\sum_{adjacent\ nodes} \kappa_{node} \frac{(T_{node}^{n} - T_0^{n})}{(\Delta i)^2} \right] \quad (6)$$

where $(\rho c)_{av}$ is the average heat capacity per unit volume for the central node, κ_{nod} is the average thermal conductivity on the line joining an adjacent node to the central node, and Δi is the distance between the two nodes.

This method requires the boundaries between different substances to lie on nodes in the grid. However, this was rarely a strong restriction. The largest problem from that constraint was that the modeled hole through the Kapton was not circular. However, in light of the agreement with experimental results, the restriction was not found to be major.

TESTS OF THE CALCULATION

The model was tested in two different fashions. The original code was compared to analytic solutions to heat conduction problems, many of which were listed in *Carslaw & Jaeger (1959)*.[5] The results were compared to the calculation method to semi-infinite solids with a circular heat source, infinite slabs of different materials, and some cylindrically symmetric solutions.

By the time the code had been compared with the models, results from laboratory experiments were available, and the program could be compared to them.[6] The agreement with experiment was excellent (see Figure 3). The top of Figure 3 shows three temperature contours for a 1 inch copper strip, insulated by 1 mil of Kapton on each side. The hole is 1/4 inch in diameter, about 1/2 inch from the end of the copper trace. The middle contour is the experimental result, while the one on the right is the program. If the program includes the averaging of the infrared camera, and accounts for the lower emissivity of copper, the contour on the left is obtained. The graph on the bottom shows the temperature as a function of time for the one inch strip. Since computer time was limited, most runs were stopped at two

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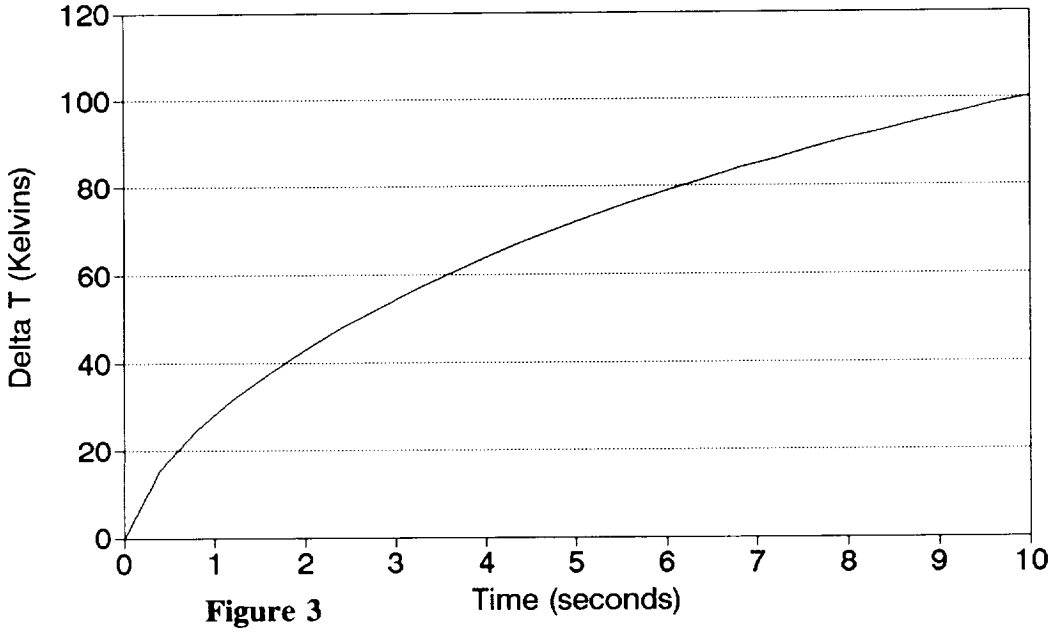

Figure 3

seconds of simulated time. The graph shows that the temperature at ten seconds is about two to three times the temperature at two seconds. It was therefore deemed appropriate to extend the calculation to models of solar cells.

The experiments covered a range of incident power from .005 W/cm^2 up to 13 W/cm^2. The computer program was able to duplicate the experimental temperature rise over the entire range of incident power. For the smallest copper strip tested, pyrolysis was seen at about 13 W/cm^2.

Two different examples of solar array geometries were examined. The first case modeled the connection between different silicon arrays, and consisted of a copper trace bounded on both top and bottom by Kapton. The second modeled the trace near the silicon, and included an electrical connection to the silicon as a possible pathway for heat to move. Since the original test was a dark test, no resistive heating was included in these models. The results are shown in Table 2.

The first part of the Table shows the temperature rise for a solar cell copper trace, both theoretically after 2 seconds, and the experimentally after 10 seconds. The calculated temperatures should be multiplied by 2 to get an expected temperature rise for 10 seconds. The calculations show that even a small variation in hole size can change the expected temperature rise. In addition, three magnitudes of incident power are shown, to show how linear the problem is. The radiative heat term should generate a non-linearity, but that effect is quite small.

The second part of the Table shows the temperature rise expected for a copper trace near silicon. All three are after 10 seconds. The two calculations show the effect of a conductive pathway between the copper and the silicon. This is to model the weld joint which connects the copper to the silicon.

Table 2 - Model of thin trace embedded in Kapton

Incident power / area	1.4 mil x 5/32 inch 1/8 " hole	1.4 mil x 5/32 inch 5/64" hole	Experiment
Time	2 seconds		10 seconds
.1 W / cm^2	.7867249 K	.4821346 K	.55 K
1 W / cm^2	7.8614550 K	4.8192897 K	7.5 K
10 W / cm^2	77.9610901 K	47.971920 K	80. K

Model of thin trace near Silicon

Incident power / area	Conductor from Copper to Silicon	No conductor from Copper to Silicon	Experiment
Time	10 seconds		
1 W / cm^2	.8 K	1.1 K	2.2 K

NASCAP/LEO, a space-charge analyzing computer program, can predict the currents expected for a biased hole exposed to the ambient Low Earth Orbit (LEO) plasma. For 1/4 and 1/2 inch diameter holes, these I-V curves are shown in Figure 4 for possible voltages and densities expected on the solar array[7]. The highest plasma densities expected for LEO orbits would be during Solar Maximum conditions, when the density can reach 4 x 10^{12} ions per cubic meter. At this density, the area of the solar array at 160 volts would collect 70 micro-amps of electron current. The model predicts a temperature rise of less than 1 degree Celsius for this incident power. This is not enough to cause significant heating of the copper or Kapton. For comparison, the laboratory test that saw pyrolysis had about 1 amp at 450 volts.

During daylight, the solar arrays are generating current through the traces. If resistive heating in the copper trace is included, the Kapton achieves an equilibrium temperature rise of about 10 degrees Celsius. In addition, the sunlight heats the arrays to about 70

temperature rise of about 10 degrees Celsius. In addition, the sunlight heats the arrays to about 70 degrees Celsius. Even an extra 1 degree Celsius from plasma heating will still not achieve pyrolysis.

CONCLUSIONS

Pyrolysis of Kapton has been duplicated in a laboratory plasma tank for a solar array type of geometry.

The calculations confirm the experimental results that the change in temperature observed in these samples is proportional to the product of incident current times the bias voltage. In LEO conditions, it does not appear likely that Kapton will pyrolyze due to incident energy from the plasma at Space Station voltages.

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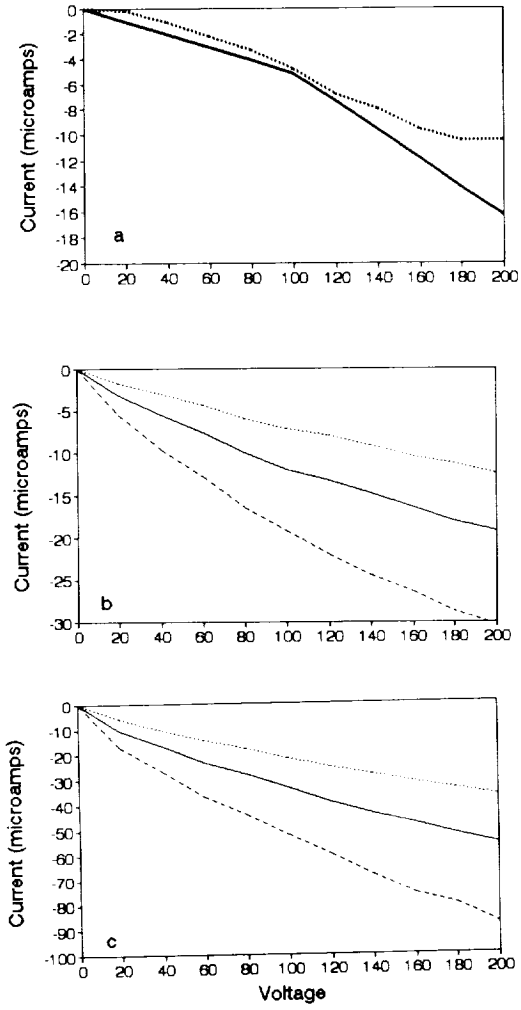

Figure 4 - (a) Dotted line is NASCAP/LEO, solid is lab result. (b) Current in space for densities of 10^6, 2 x 10^6, and 4 x 10^6 electrons/cc, 1/8 inch hole. (c) Current in space for densities of 10^6, 2 x 10^6, and 4 x 10^6 electrons/cc, 1/4 inch hole.

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