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RECTENNA THERMAL MODEL DEVELOPMENT

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Abstract

Deploying rectennas in space requires adapting existing designs developed for terrestrial applications to the space environment. One of the major issues in doing so is to understand the thermal performance of existing designs in the space environment. Toward that end, a 3D rectenna thermal model has been developed, which involves analyzing shorted rectenna elements and finite size rectenna element arrays. A shorted rectenna element is a single element whose ends are connected together by a material of negligible thermal resistance. A shorted element is a good approximation to a central element of a large array. This model has been applied to Brown's 2.45 GHz rectenna design. Results indicate that Brown's rectenna requires redesign or some means of enhancing the heat dissipation in order for the diode temperature to be maintained below 200° C above an output power density of 620 W/m². The model developed in this paper is very general and can be used for the analysis and design of any type of rectenna design of any frequency.

Introduction

One of the means of powering space missions is to transmit the power at microwave or millimeter wave frequencies. In order to receive this power and convert it to DC a rectifying antenna or rectenna is necessary at the end where it is desired to make use of this beamed power. To date rectennas have been designed and built to be used on high altitude aircraft or for the solar power satellite where they would be deployed in terrestrial environments. Space missions would require higher power densities than the applications rectennas were originally designed for. In addition in space, thermal convection which is available in terrestrial environments is absent, confining heat dissipation to radiation alone. It is thus necessary to develop a methodology to conduct thermal analysis of rectennas deployed in space environments, which can lead to a better understanding of rectenna performance in space and yield higher reliability rectennas, which is the subject of this paper.

Model of a single unit cell

A rectenna array consists of several parallel sub-arrays of rectenna elements. A typical rectenna element consists of a half-wave dipole, transmission lines, low pass filters, a Schottky barrier diode and DC buses. *Figure 1* shows a schematic representation of Brown's 2.45 GHz (referred here on to as the 2.45 LP or linear polarized rectenna) rectenna array. Each sub-array can be thought of as being composed of a repeat pattern, this being the rectenna element. The substrate on which the circuit is etched is referred to as the foreplane. Microwave power is incident on the foreplane, some of which is converted to useful DC by the circuit and the rest goes through the substrate. It is necessary to redirect as much of this power as possible to the foreplane to ensure high conversion efficiency. This is accomplished by the use of a reflecting plane which is placed approximately quarter of a wavelength (the wavelength of the microwave radiation) behind the foreplane. In order to provide structural support to the reflecting plane and prevent any electrical interaction between the circuit and the reflecting plane an electrical insulator is placed between the foreplane and the reflecting plane (known as the spacer).

A single rectenna element together with the underlying substrate, the spacer and the reflecting plane is the unit cell for the purposes of computations. In the case of the 2.45 LP rectenna the circuit is made of copper, the substrate is Kapton F, the spacer is styrofoam or polyurethane and the reflecting plane is aluminized Kapton. It is necessary to determine both the temperature distribution within each element of the sub-array and the diode temperatures of all of the elements of the sub-array. In order to be able to do this, initially a single element is modeled. A mesh of the circuit and underlying materials is constructed using the mesh generator INGRID¹ and is shown in *Figure 2*. The copper circuit is etched on the substrate and protrudes out approximately 2 mils above the substrate. The diode has two gold ribbons at either end, by which it is bonded to the circuit. The bypass filter is depicted as being above the transmission line, while it actually is located behind the foreplane. This is done purely to facilitate ease of constructing the mesh. The diode is the principle heat source in the circuit. Incident microwave not converted to DC (due to the inefficiency of the diode) gets converted to heat in the diode. The diode is an asymmetrically placed heat source in the rectenna element (unit cell) because of which there is heat flow across the edge of the unit cell. In fact other than ensuring that all the components of an element are contained in the unit cell, the choice of where to locate the unit cell boundaries is quite arbitrary. In the case shown in *Figure 2*, the boundary is chosen as an alternative to modelling the unit cell from dipole to dipole. Choosing the latter option could result in step discontinuities in the solution.

The diode is a Schottky barrier diode packaged in a ceramic casing. Brown reported² that there was only negligible heat flow from the ohmic contact side of the diode (lid side) and he suggested that repackaging the diode in the ceramic casing (as opposed to the original glass casing) would

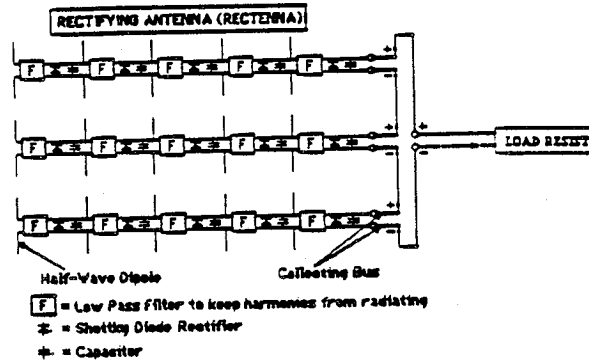


Figure 1. Schematic of Brown's 2.45 LP rectenna array. Each unit of the repeat pattern in the array is the rectenna element (unit cell). Components of the rectenna element are also shown.

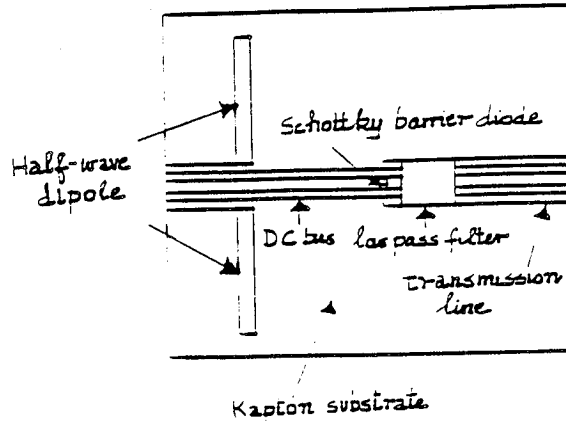


Figure 2. Mesh generated picture of the rectenna unit cell constructed using INGRID. Shown are the foreplane and circuit details. The spacer and reflector lie below the foreplane. The cartesian co-ordinate system is shown to the right, with the z direction pointing outwards from the plane of the page.

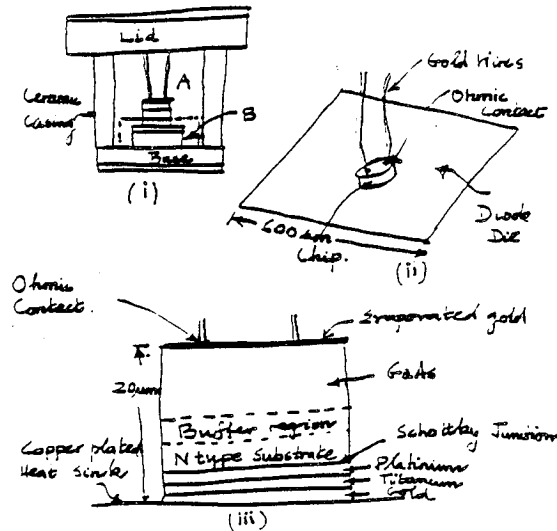


Figure 3. (i) Shows the schematic of the Raytheon Schottky barrier diode. Figure (ii) shows the diode die and the chip which is soldered to the base. Figure (iii) shows the details of the chip and the heat sink.

substantially increase the heat flow from the lid side. While the heat transfer characteristics are improved somewhat due to the repackaging, the heat flow from the lid side continues to be negligible. The diode is modeled as three separate anisotropic elements, one element each for the lid, the base and the alumina ceramic case. The two gold ribbons at each end of the diode that are used to connect the latter to the circuit are modeled as two isotropic elements. *Figure 3* shows the details of the Raytheon Schottky barrier diode. These details are compilation from various reports papers authored by William Brown and an analysis of the diode conducted by the Communications Research Centre.³ *Figure 3* (i) shows the schematic of the diode. The diode die which is shown in *Figure (ii)* is soldered onto the base and covered with the alumina ceramic casing. The wires from the chip are then connected to the lid. Two gold ribbons are connected to the base and lid, which are soldered to the circuit. *Figure (iii)* shows the different regions of the chip and the heat sink.

Most of the heat is dissipated in the Schottky junction shown in *Figure (iii)*. The region below the junction but above the base is called region B. The region above the junction, including the chip, the ohmic contact and gold wires is termed region A. The reason that the heat flow on the lid side is poor is because of the 1 mil thick gold wires (2) which have a very large thermal resistance. The conductivity of the individual elements is determined as follows:

- (i) Total series resistance for regions A and B are determined (R_A and R_B). R_A also includes a radiant heat transfer component from the base to the lid.
- (ii) Thermal conductivities (K_x , K_y and K_z) is determined for the base, the alumina and the lid. (These three parts are in turn composed of sub-components of different materials).
- (iii) The thermal conductivities of the base, lid and the casing are changed to accommodate the change in their areas on account of modeling them as rectangular elements (as opposed to the original circular c/s).
- (iv) The resistance R_A is added to the lid, modifying the thermal conductivity of the lid in the y direction (K_y).
- (v) R_B is added to the base, thus changing K_y of the base.

The bypass filter (subsequently referred to as the interconnect) is originally located below the Kapton. However for ease of modeling it is moved over the copper transmission lines shown in *Figure 2*. From a thermal standpoint, the interconnect conducts heat from the transmission line on the base side to the transmission line on the lid side, thus doubling the effective radiant dissipation area available to the diode. In the absence of the interconnect, the heat would only be dissipated by the transmission line on the base side, resulting in substantially higher diode temperature. The interconnect in effect compensates for the fact that the diode only dissipates heat on one side (the base). The interconnect is modelled as number of anisotropic elements. The thermal conductivities of the interconnect are determined as follows:

- (i) In x and y direction the heat flow is a parallel flow. For example the thermal resistance in the x direction R_x is

$$\frac{1}{R_x} = \frac{1}{R_k} + \frac{1}{R_c}$$

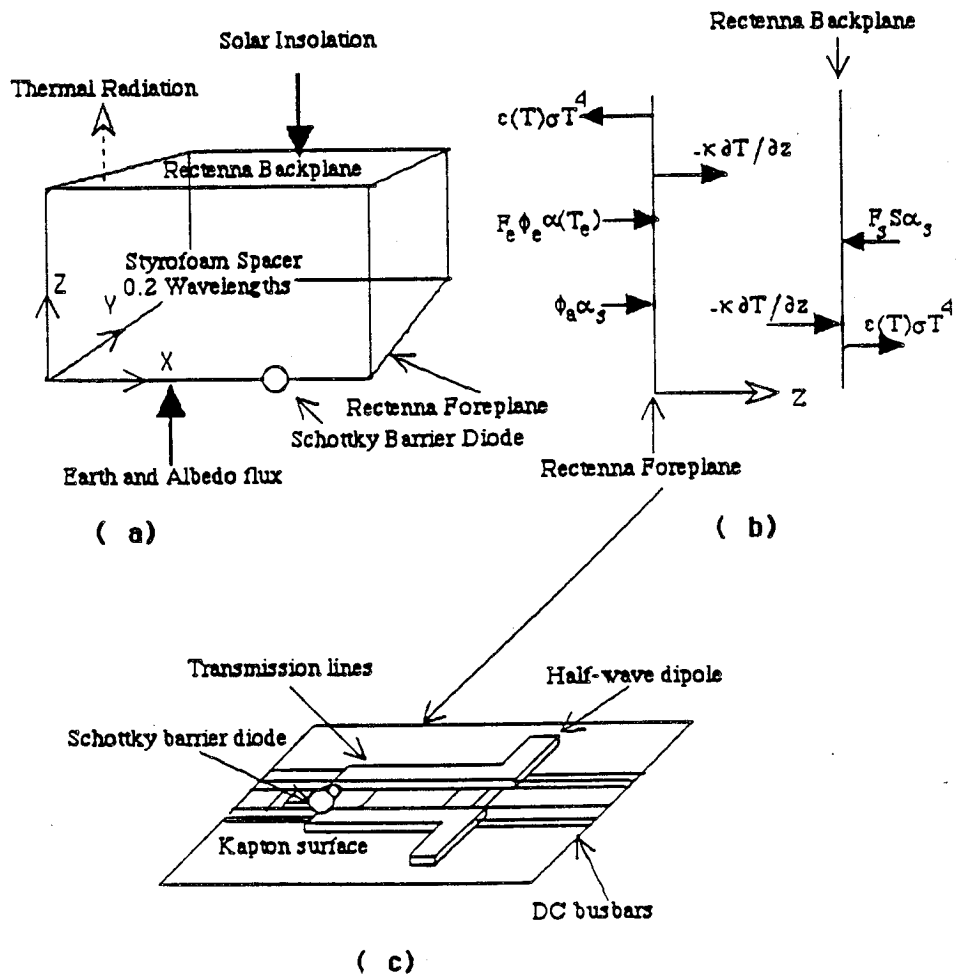


Figure 4. (a) shows a unit cell of the rectenna and the various incoming and outgoing fluxes. The Schottky barrier diode is the main source of heat in the diode. Figure (b) shows the energy balance on the foreplane and the reflector plane. Figure (c) shows the details of the circuit on the foreplane.

Where R_k and R_c are resistance of the Kapton and copper which make up the interconnect. Since the thickness of Kapton is very small, $R_k \rightarrow \infty$, therefore $K_x \approx K_c$ and $K_y \approx K_c$.

(ii) In the z direction, the heat is series flow, therefore:

$$R_z = R_k + R_c$$

Since the areas are the same and the thickness of copper and Kapton are of the same order of magnitude and $K_c \gg K_k$ therefore:

$$K_z \approx K_k$$

That is the amount of heat conducted through the interconnect is determined by Kapton, while across by copper. Besides heat dissipation in the diode, there is Joule heating in the DC buses, when current passes through them. This Joule heat is modeled as volumetric heat generation in the heat conduction equation. The rectenna itself is assumed to be in a low earth orbit, due to which solar flux is incident on the reflector plane and albedo and earth flux are incident on the foreplane. Albedo flux is the fraction of the incoming solar radiation reflected back by the clouds and is given by:

$$F_a = Sa$$

where S is the solar constant and a is the albedo coefficient (Agrawal, 1986)⁴. An annual mean value of a ($= 0.32$) is used in all calculations. The earth absorbs a part of the incoming solar radiation and emits infrared radiation ($F_r = 237 \text{ W/m}^2$) which is assumed to be incident on the rectenna foreplane. *Figure 4*, depicts the unit cell with the associated incoming and outgoing fluxes and the energy balance on the foreplane and reflector plane. A 3D finite element heat transfer code TOPAZ3D⁵ is used to solve the anisotropic heat conduction equation throughout this paper. Results (temperature contours) of a run at a power level of 218 mw (dissipated in the diode) for an unshorted unit cell are displayed in *Figure 5*. The contours are asymmetric about the x axis near the diode because of the unequal dissipation of heat close to the diode. The diode temperature is 402 K at a dissipation of 286 mw, which corresponds to about 1.76 watts of output power per diode (or about 352 W/m₂ output) corresponding to a 200 ohm load resistance.

Model of a shorted unit cell

The diode is an asymmetrically placed heat source within each rectenna element (unit cell) because of which there is heat flow across the edges of the unit cell. Thus results from modeling a single unit cell are not representative of a rectenna element in a sub-array. In order to overcome this problem, the edges of the unit cell (of the kind developed in the last section) are "shorted" together when performing the computation. Shorting is an artificial construct used just for modeling purposes and provides a means determining the temperature distribution of a rectenna element

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a sing unshoed
time = 0.10000E+01
contours of topaz3d temperature
min= 0.298E+03 at node 803
max= 0.402E+03 at node 958

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contour values
0.06E+02
0.17E+02
0.28E+02
0.39E+02
0.50E+02
0.61E+02
0.72E+02
0.83E+02
0.94E+02

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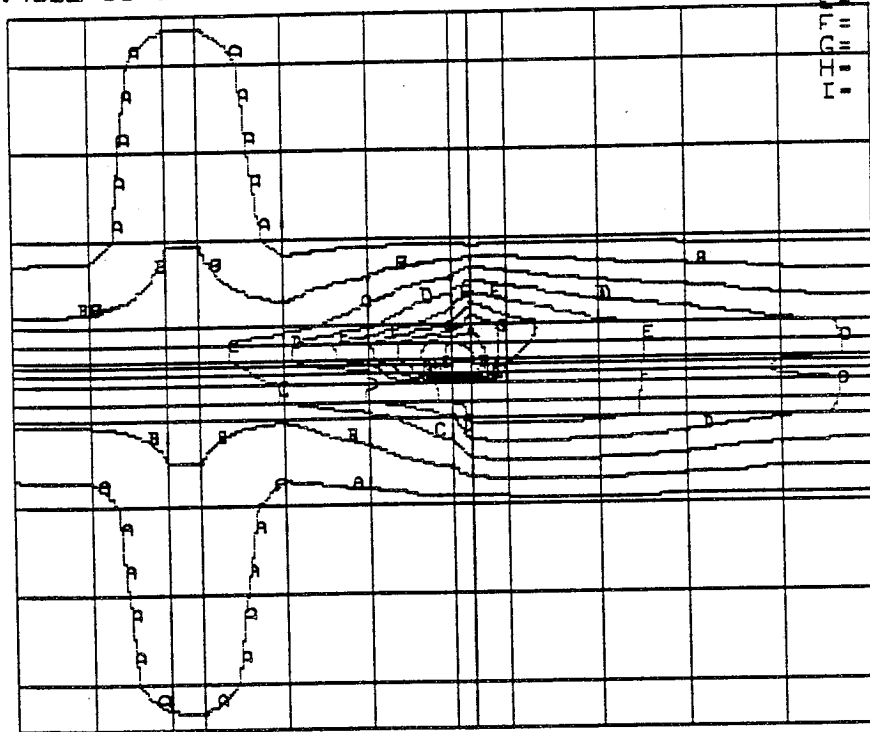


Figure 5. Temperature contours of 3D thermal model of a single rectenna unit cell. Diode temperature is 402 K for 286 mW of heat dissipation. . The contours are not symmetric near the diode because of the unequal dissipation of heat on either end of the diode.

in the center of a large array. It is used in place of actually wrapping the unit cell around. Thus the short should have negligible or zero thermal resistance. Since

$$R = \frac{\Delta (xV_yV_z)}{KA} = \frac{\Delta n}{KA}$$

K is chosen large enough that $R \approx 0$.

In the case of the rectenna unit cell each of the different materials must be connected with "shorts" of thickness corresponding to that specific material. For example the outermost layer of copper must be connected by a short which corresponds to the thickness of the transmission lines. The copper short encases the shorts for the other materials, namely the Kapton and the spacer. *Figure 6* shows the mesh for all the materials with the copper short discontinuous at the top. The region where the gap occurs in the copper is deleted in the next stage and the unit cell mesh (developed in the last section is put in the place of the material removed). *Figure 7* shows the plan view of the shorted unit cell with the temperature contours superimposed on the foreplane for a dissipated power level of 286 mw. As expected the temperatures on either end of the unit cell where the short begins are equal (317 K, indicated by the contour line B in *Figure 7*) and the temperature of the diode is 399.59 K (a 3.K difference from the unshorted case at the same power level).

Model of a three cell array

In the case of large arrays, there will not be much variation in the diode temperature from element to element, except at the edges. However, in finite arrays there is expected to be variation in diode temperatures. In order to determine this temperature variation, a finite size array, consisting of three elements is modeled. The unit rectenna unit cell developed earlier is used and two more similar unit cells are created. These three cells are then connected together and appropriate coordinates are specified when linking them together. Flux and radiant boundary conditions as before are specified and the heat conduction equation is solved for the three cell array. *Figure 8* shows the mesh and the temperature contours for the three unit cell array at a dissipated power level of 286 mw. Joule heating is included in this computation. The diode temperature increase linearly from the left to the right (with the left at 399.60 K, the central diode at 400.72 K and the right at 403.37 K) at a dissipation of 286 mW in the diode. Combined results from several computations showing diode temperature versus heat dissipated for the 2.45 LP rectenna are plotted in *Figure 9*.

Conclusions

There is good agreement between the diode temperature in the shorted case and the diode in the central element of the three cell array. If one assumes that 200°C (473 K) is an upper limit on the diode temperature to ensure reliable rectenna performance, (as suggested by Brown) then from *Figure 9*, this limits the heat dissipation in the diode to approximately 546 mW or 0.55 Watts. At 85% conversion efficiency of microwave to DC, this corresponds to an output power density of 620 W/m². This suggests that for higher power densities the 2.45LP rectenna should either be redesigned to increase heat dissipation or some means of augmenting the heat transfer out of the diode should be provided. The methodology developed in this paper can easily be adapted to analyzing any kind of rectenna designs at any frequency.

References

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- ⁴Agrawal, B.N. *Design of Geosynchronous Spacecraft*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1986).
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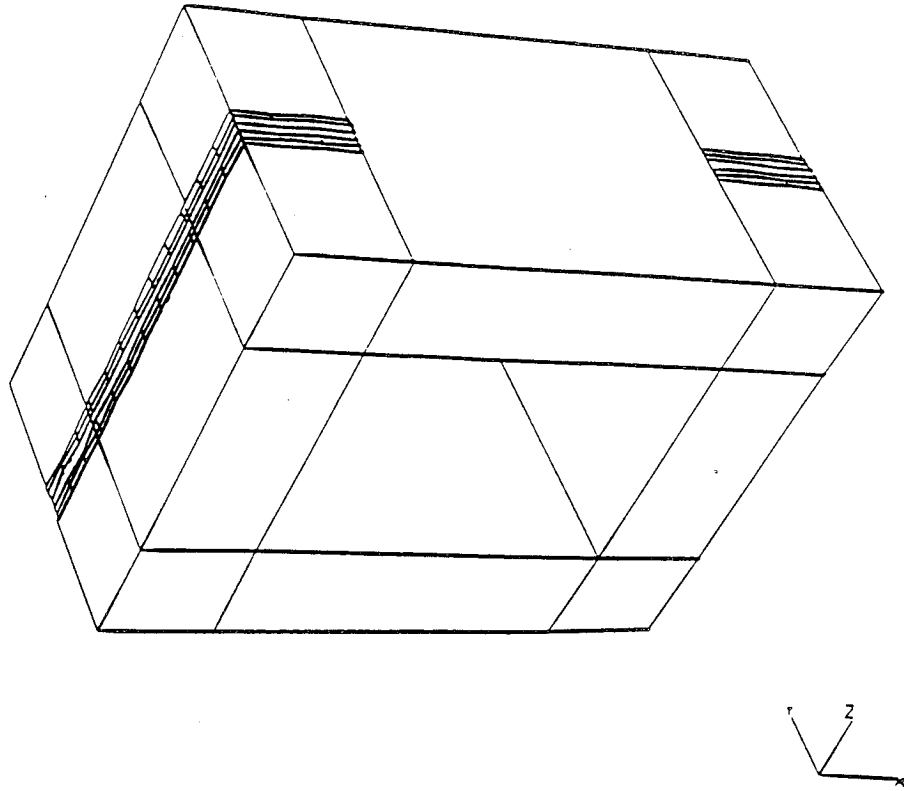


Figure 6. Mesh generated picture of the "short" for all the materials of the the rectenna unit cell developed using INGRID. The copper circuit "short" encases all other materials and the location at the top where it does not exist is the region where the rectenna unit cell is emplaced prior to computation in the case of the shorted cell.

```

time = 0.10000E+01
contours of topaz3d temperature
min= 0.298E+03 at node 753
max= 0.400E+03 at node 936

```

```

contour values
A = 0.06E+02
B = 0.17E+02
C = 0.28E+02
D = 0.38E+02
E = 0.49E+02
F = 0.59E+02
G = 0.70E+02
H = 0.80E+02
I = 0.91E+02

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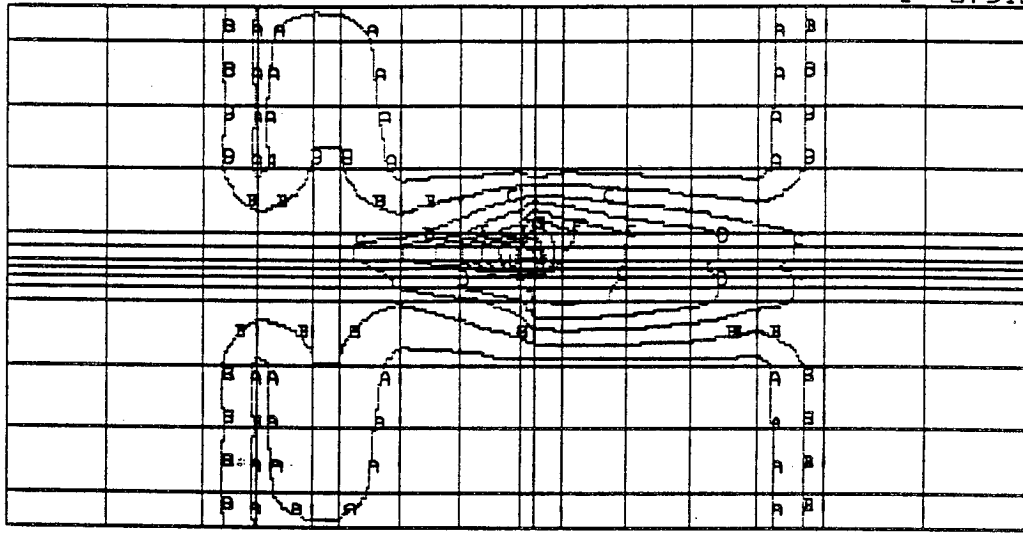


Figure 7. Plan view of the shorted unit cell and superimposed temperature contours. Diode temperature is 399.59 K for a dissipation of 286 mW. Temperatures at the either edges of the unit cell (contour B) are the same (317K) due to shorting.

time = 0.10000E+01
contours of topaz3d temperature
min= 0.298E+03 at node 771
max= 0.403E+03 at node 2742

contour values
A= 0.07E+02
B= 0.18E+02
C= 0.28E+02
D= 0.39E+02
E= 0.50E+02
F= 0.61E+02
G= 0.72E+02
H= 0.83E+02
I= 0.94E+02

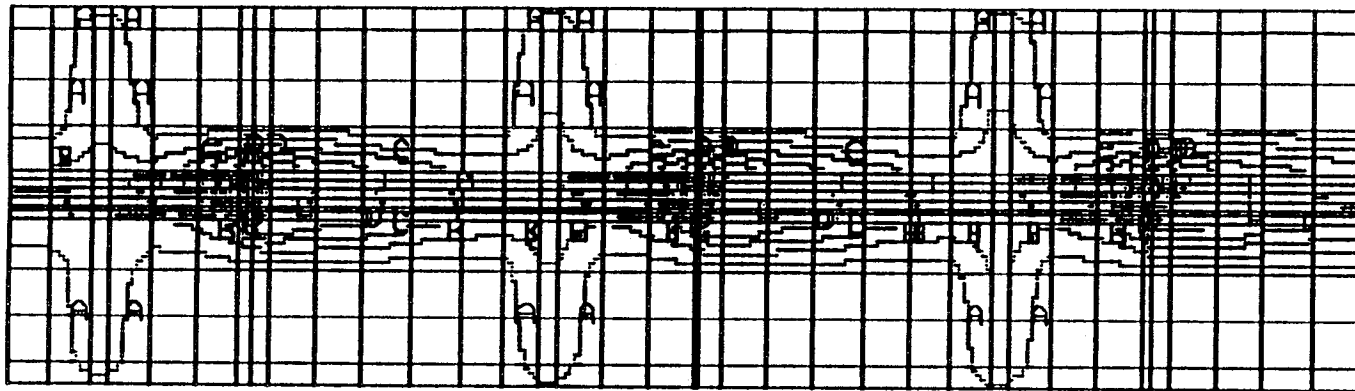


Figure 8. Temperature contours for an array of three rectenna unit cells. The computation is done for 286 mW of diode dissipation. The third diode (from left to right) has the maximum temperature of 403.37° K.

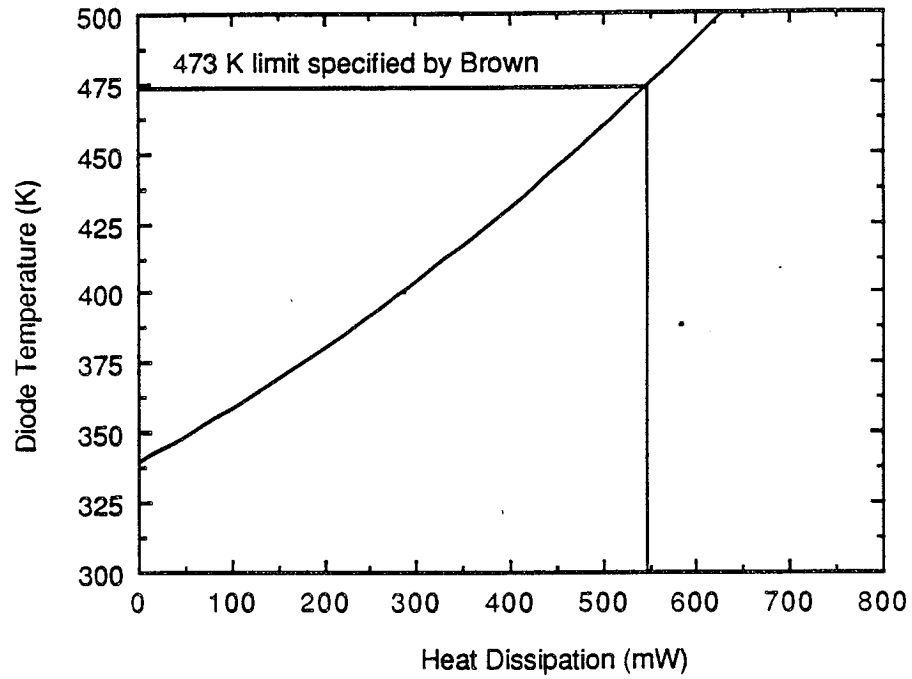


Figure 9. Combined results from many computations showing diode temperature versus heat dissipated in the diode. Also shown is the 473 K upper temperature specified by Brown and corresponding maximum dissipation of 0.55 Watts.