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To: Packaging and Thermal Engineers Involved in the Design and Packaging of IC Chips.
From: Gordon N. Ellison, President, Thermal Computations, Inc.
Objective: Summarize the Methodology Used to Analyze the Enerdyne POLARA™ Heat Spreader Technology.

I. Introduction

This document provides a detailed explanation of the modeling methods used to analyze the Enerdyne Polara™ Heat Spreader Technology. This computer based evaluation of heat spreader material properties and resulting comparison analysis is intended to be an insightful proof of principle. An ancillary benefit of this scientific approach is that significant trends and design guidelines are often readily obtained, particularly if the analysis tool does not require extensive input for every parameter variation of interest.

II. Principal Software Used

The software used for most of the analyses of the Enerdyne Heat Spreader Technology is the FlexPDE program [1], a remarkably flexible and easy to use tool for solving most partial differential equations encountered in Physics and Engineering. The two-dimensional version of the software was used for the heat spreader problems. This required setting up problems in a cylindrical coordinate system using axial symmetry. Therefore a problem with a square heat source, square heat spreader, square substrate, etc., required the conversion of each square piece to one of cylindrical geometry with thickness identical to the square device but a radius that results in a device with cross-sectional area equal to that of the square device, i.e. a

radius $r = \sqrt{A/\pi}$ where A is the area of the square.

FlexPDE uses the finite element method (FEM) to solve one or more user-input partial differential equations for either steady state or time-dependent problems. Regions of various materials and properties are readily input by user-input lines and arcs enclosing these regions. Boundary conditions are described by inputting text along with the material bounding lines. The benchmark model discussed in the following section was also analyzed using the TAMS (Thermal Analyzer for Multilayer Structures) [2, 4]. TAMS is based on a steady-state solution of the partial differential equation for heat conduction using a Fourier series technique.

Engineers at Enerdyne Solutions have used the thermal network analyzer TNETFA (Thermal NETwork Flow Analyzer) to benchmark a packaging design more complex than can be solved using TAMS [3,4]. The results were found to agree with the FlexPDE data within an acceptable tolerance.

III. Benchmark Models

The purpose of software benchmarks is typically one of verifying the accuracy of the software and also ensuring that the user is correctly using the program as much as possible. In the case of evaluating the FlexPDE software it was especially important to ensure that heat source and boundary condition input was understood.

Problem input for FlexPDE is not difficult for the Enerdyne Heat Spreader Technology, with perhaps the exception of non-zero heat flux input and convective boundary conditions. FlexPDE uses a *natural* boundary condition definition that is consistent with the internal mathematics of the software. Volumetric heat sources distributed within the problem geometry are more straightforward with less risk of input error.

The geometry illustrated in Figure 1 is used for this basic benchmark. The problem is that of a single layer of material with a 1.5 cm square source on one side and a convecting surface on the other side. The latter is specified as a thermal resistance of $0.5 K/W$ from surface to ambient. The surface heat source is $10 W$. All remaining surfaces are adiabatic. The illustration also indicates a source that is input in TAMS as a *surface source*, but in FlexPDE as a volumetric source of very small thickness (5.0×10^{-3} cm). The source in TAMS is activated or deactivated by giving it a total of $20 W$ or $0 W$, respectively.

The TAMS program is able to analyze the rectangular geometry illustrated, but as discussed in II, the version of FlexPDE used analyzes only two-dimensional axisymmetric problems. The equivalent FlexPDE geometry was therefore a circular source on a circular substrate. The geometry actually used in TAMS analyzed one quadrant of the problem because of the symmetry across lines $X=0$, $Y=0$ shown in Figure 1.

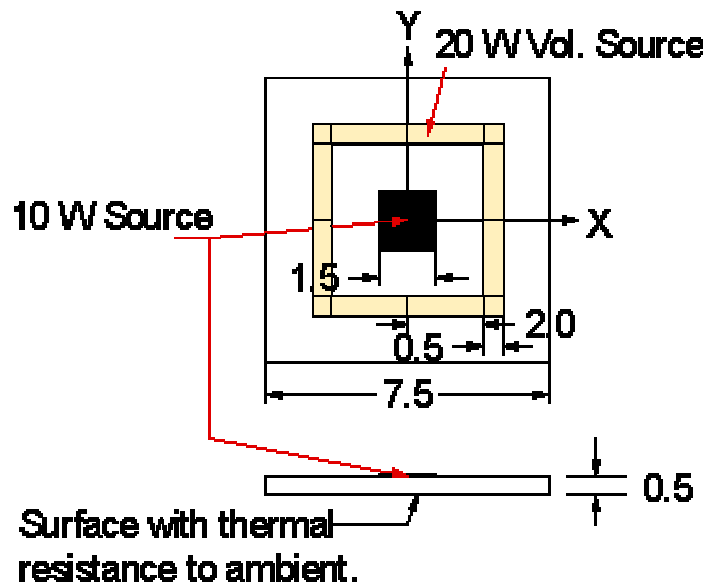


Figure 1. Layout of benchmark problem.

Coordinate axes consistent with TAMS. All dimensions in cm.

All surfaces are adiabatic except the base (with specified thermal resistance) and source regions.

The meshed FEA model in cylindrical coordinates is illustrated in Figure 2. The left edge of the meshed geometry is also a vertical line of symmetry that runs through the 20 W source. Both sources in this model are at the bottom edge and the convecting surface is at the top of the mesh. The volumetric source is approximately in the center of the illustration. As expected, the mesh density is greatest in the vicinity of the sources. The model resulted in approximately 9600 nodes and 4600 elements.

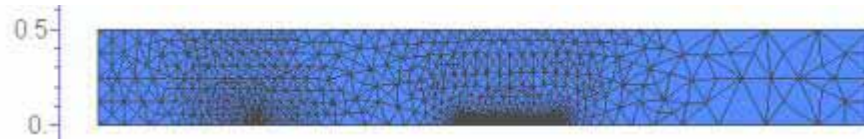


Figure 2. FEM mesh for benchmark model with volumetric source enabled.

Surface and volumetric sources at left, bottom and center, bottom, respectively, of illustration.

The computed results from both programs are shown in Figure 3 for the condition of the *volumetric source disabled*. Temperature plots from the device center on both the source and convecting surfaces are shown. Whereas FlexPDE can easily produce temperature contours through an entire cross-section, TAMS can only provide surface temperatures. The two programs produce nearly identical results, particularly for the case of the disabled volumetric source. In this instance there is some difference in the results from TAMS and FlexPDE near the substrate edge, but this is to be expected since the two problems solved are not using exactly the same geometry, i.e. one uses rectangular geometry and the other used cylindrical geometry. There is also a slight difference from the two programs at the source edge (0.75 cm in Fig. 3) for the same reason.

Similarly, the computed results from the programs are shown in Figure 4 for the condition of the *volumetric source enabled*. In this case it appears that there is a greater difference in the results from the two programs, but it is less than two percent. Part of this small discrepancy is due to the fact that it is not exactly clear at what radial location the volumetric source should be placed in the cylindrical geometry of FlexPDE. It was decided to use a radial distance of $r=2.0$ cm and $\Delta r = 0.5$ cm in FlexPDE and $x = y = 2.0$ cm, $\Delta x = \Delta y = 0.5$ cm in TAMS.

Filled temperature contours from the FEA model with the volumetric source activated are shown in Figure 5 for completeness.

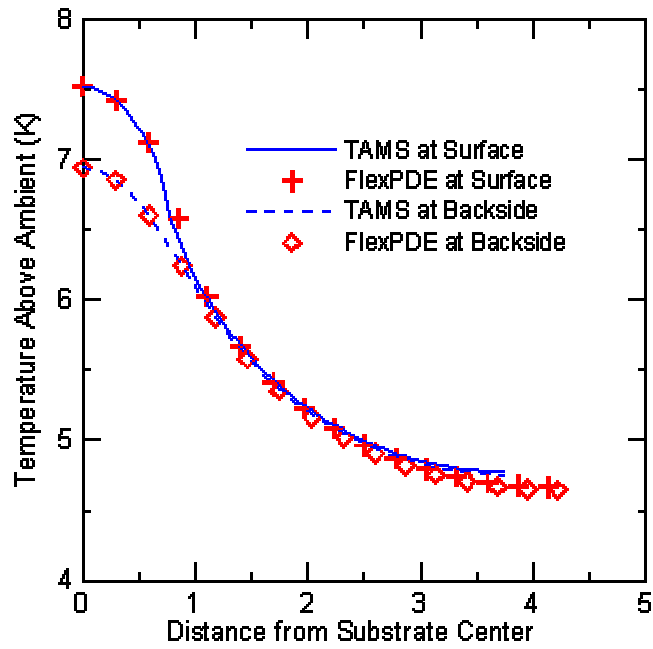


Figure 3. Benchmark model temperature profiles at $Y=0$ from $X=0$ to substrate edge. Volumetric source disabled

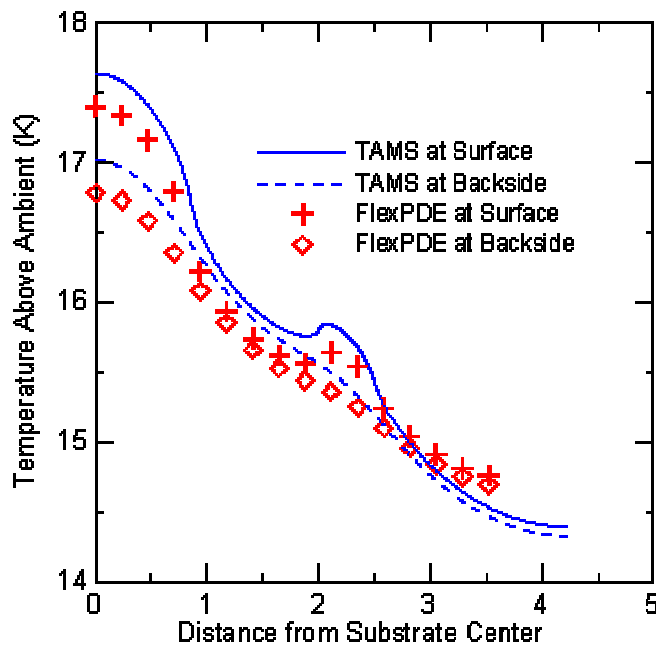


Figure 4. Benchmark model temperature profiles at $Y=0$ from $X=0$ to substrate edge. Volumetric source enabled.

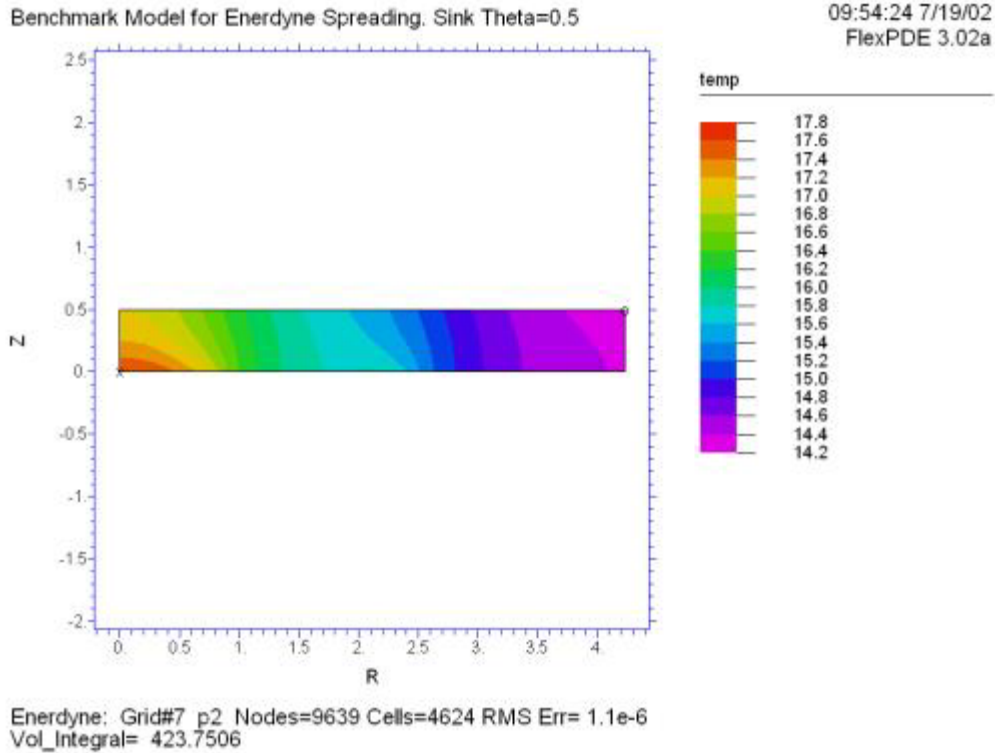


Figure 5. Temperature contours for FEM benchmark model
Volumetric source enabled.

IV. Typical Model Problem

Analysis of a complete Enerdyne Heat Spreader device obviously entails greater geometry complexity due to simulation of an IC die, interface attachment materials, etc. Figures 6 and 7 illustrate a typical meshed model and filled temperature contours for such a situation.

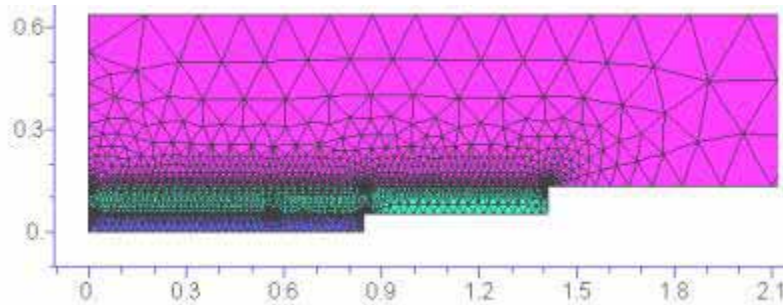


Figure 6. A portion of a meshed Enerdyne Heat Spreader model

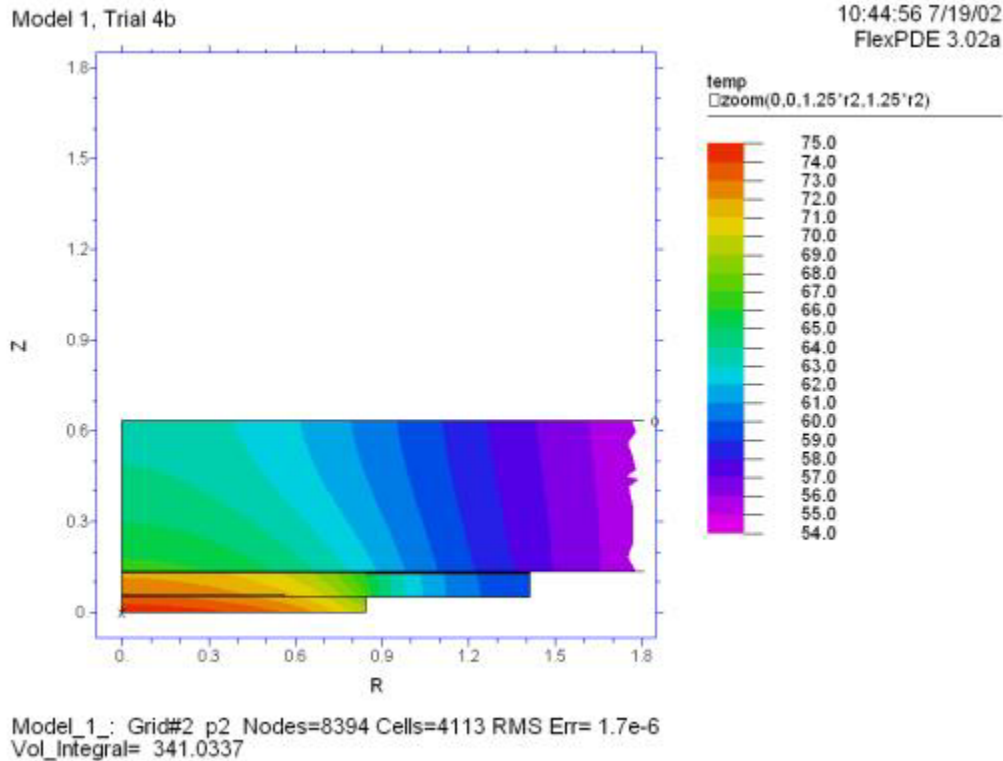


Figure 7. Enlarged view of filled temperature contours of an Enerdyne Heat Spreader model.

V. Summary and Comments

The comparison between the Fourier series TAMS model with the FEM FlexPDE model is excellent, considering the fact that one used rectangular geometry and the other uses cylindrical geometry. Certainly it has been established that the convective boundary conditions, surface heat source data and volumetric heat source input methods are correct.

Although full three-dimensional models are optimal for asymmetrical package designs, the two-dimensional, axisymmetric, FlexPDE models achieved the objective of comparing the thermal performance of Polara™ with typical spreader materials.

VI. Biography

Gordon N. Ellison has in excess of thirty years experience in the analysis and design of electronic components and enclosures. These problems have included mainframe style computers, bench top and portable oscilloscopes, engineering workstations, hybrid and multi-chip modules, IC chips, infrared imaging systems, and cryogenically cooled electronics.

Mr. Ellison's industrial experience has been largely with the NCR Corporation as a Technical Specialist, and eighteen years with Tektronix, Inc. as a Chief Scientist and Tektronix Fellow.

Gordon Ellison is currently an Adjunct Assistant Professor of Mechanical Engineering at Portland State University, a Senior Life Member of the IEEE, and is President of Thermal Computations, Inc. a small consulting firm from which he provides consulting, advising, and

software to the electronics industry. He has been presented with the IEEE SemiTherm Significant Contributor Award, earned an IEEE SemiTherm Best Paper of Conference award, and is a previous Associate Editor of the Electronics Cooling magazine. He has numerous papers and presentations published concerned with electronics cooling and is the author the text, *Thermal Computations for Electronic Equipment*.

VII. Selected References

1. FlexPDE, PDE Solutions Inc., Antioch, CA. Website: www.PDESolutions.com.
2. Ellison, G.N., Thermal Analysis of Circuit Boards and Microelectronic Components Using An Analytical Solution to the Heat Conduction Equation, an Invited Lecture presented at the 12th Annual Semiconductor Thermal Measurement and Management Symposium, Austin, Texas, March 5-7, 1996.
3. Ellison, G.N., "Thermal Analysis with Affordable Programs", presented at the 5th International Electronics Packaging Conference, Orlando, Florida, 1985.
4. Thermal Computations, Inc., Newberg, OR. Website: www.ThermalComputations.com

[Enerdyne Note to Reader: The models utilized identical chip power source geometry and distribution, material thickness, heat spreader and heat sink geometry, sink interface material properties, convection coefficients and thermal conductivity values, judiciously selected from industry accepted sources. Within all four models, the attached FlexPDE graphs illustrate the lowest IC die temperature is achieved by the Polara™ (Trial 3) heat spreader technology.]

Appendix I: TAMS Input File Including Enabled “Volumetric” Source

One Quadrant of 1.5 cm sq. 10.0 W source on 7.5 cm sq. substrate.

```
1
0          300
300        3.7500E+00      3.7500E+00
1.2500E-01  1.2500E-01      1.2500E-01
1.2500E-01  1.0000E-10      3.5560E-02
0.0000E+00  2.0000E+00      2.0000E+00
2.0000E+00  2.0000E+00
4          0
0
0          0.0000E+00      7.5000E-01
0.0000E+00  7.5000E-01      2.5000E+00
2.0000E+00  5.0000E-01      0.0000E+00
2.0000E+00  2.2222E+00      2.0000E+00
5.0000E-01  2.0000E+00      5.0000E-01
5.5556E-01  0.0000E+00      2.0000E+00
2.0000E+00  5.0000E-01      2.2222E+00
1          2          3          4
```

Appendix II: FlexPDE Input File Including Enabled Volumetric Source

TITLE 'Benchmark Model for Enerdyne Spreading. Sink Theta=0.5'

SELECT

errlim=1e-5

COORDINATES

ycylinder('r','z')

SELECT

{NODELIMIT=400}

VARIABLES

temp

DEFINITIONS

a=7.5 {x-dimension of square substrate in cm}
L=0.5 {Substrate thickness in cm}
temp_amb=0 k=2.0 {Ambient T seen by sink in C, substrate k in "W/cm*C"}
Theta=0.5 {Substrate Sink-to-Ambient Thermal Resistance in C/W}
power_in=10.0 {Heat source dissipation in W}
Asub=a^2 {Planar area of substrate}
r2=sqrt(a^2/pi) {Radius of circle with area = to substrate area}
r1=sqrt(delta_x^2/pi) {radius of circle with area = to source area}
ri_Reg_2=2.0 {Inner radius of region 2}
ro_Reg_2=2.5 {Outer radius of region 2}
p=.001
th_Reg_2=p*L {Fraction of total thickness, thickness of region 2}
Q2=20
QV2=Q2/[pi*(ro_Reg_2^2-ri_Reg_2^2)*th_Reg_2] {Heat dissipation, heat dis./vol. of region 2}
delta_x=1.5 {x-dimension of square source in cm}
h=1/(Theta*Asub) {Effective h in "W/cm^2*C"}
fluxd_in=power_in/(pi*r1^2)
fluxd_r=-k*dr(temp)
fluxd_z=-k*dz(temp)
fluxd=vector(fluxd_r,fluxd_z)
fluxdm=magnitude(fluxd)
QV=0.0

EQUATIONS

$(1/r)*dr(-r*k*dr(temp)) + dz(-k*dz(temp))=QV$

BOUNDARIES

region 1 'Main'
start(0,0) natural(temp)=-fluxd_in line to (r1,0)
natural(temp)=0 line to (r2,0) to (r2,L)
natural(temp)=h*(temp-temp_amb) line to (0,L)
natural(temp)=0 line to finish

```
region 2 'Volumetric Source' QV=QV2
start(ri_Reg_2,0) line to (ro_Reg_2,0) to (ro_Reg_2,th_Reg_2) to (ri_Reg_2,th_Reg_2) to
finish
```

PLOTS

```
grid(r,z)
grid(r,z) zoom(0,0,4*r1,3*r1)
{contour(temp)} contour(temp) Painted
contour(temp) zoom(0,0,0.1,0.1) {painted}
contour(fluxdm) vector(fluxd) norm
contour(fluxd_r) contour(fluxd_z)
elevation(temp) from (0,0) to (r2,0) export format "#x#b#1" file="T_vs_X_at_0.txt"
elevation(temp) from (0,L) to (r2,L) export format "#x#b#1" file="T_vs_X_at_L.txt"
```

END

Enerdyne Solutions
POLARA™ Heat Spreader Technology
Thermal Simulation Notes

Solutions Simulated

The specific heat spreader types include: The current copper heat spreader solution, AlSiC composite competitive solution, and the POLARA™ series solution with high and low power versions. The AlSiC composite material solution was selected as a competitive example because it offers the highest cost/performance benefit, second only to the POLARA™ series solutions. The POLARA™ high and low power versions (differing thermoelectric input power levels, both with a COP of 5) give the designer the option to select higher performance or lower input power.

Graph Descriptions

The Die Temperature Profile graph includes junction side chip temperatures. The chip's central point (located at the zero point) provides the peak (maximum) temperature data in all solutions presented. This peak temperature limits the entire chip's operating temperature.

The Savings Over Copper (Cu) graph includes heat spreader material/technology, interface and heat sink costs.

Simulation Variables

IC package material variables included mechanical specifications and material properties.

Thermoelectric variables included Seebeck coefficients for Polara™ materials and the magnitude of the Peltier effect.

Due to the proprietary nature of the case examples, certain package specifications were judiciously approximated. Die assumptions include: square geometry, uniform heat flux and that all heat energy is removed from the backside. Specific settings utilized for this thermal simulation can be viewed here.

Benchmark Simulation

A benchmark simulation was run with ALGOR software and the results (available in Appendices) were found to agree with the FlexPDE data.

Conclusion

POLARA™ heat spreaders reduce overall thermal solution costs and allow higher chip power levels. POLARA's higher thermal transport performance boosts the dissipation efficiency of fan/heat sink solutions.

Product Examples

Model 1: Intel Pentium 4 Microprocessor

Overall Inputs:

Source: 1.5 cm, .05 cm thick, $k=.90$ w/cm-K, **65 Watts**;
Die attach: 1.5 cm, .00254 cm thick, $k=$ (See specific trial inputs)
Spreader: 2.5 cm, .08 cm thick, $k=$ (See specific trial inputs)
Grease: 2.5 cm, .00254 cm thick, $k= .01$ w/cm-K;
Heat sink: 7.5 cm, .5 cm thick, $k= 2.0$ w/cm-K.
Heat sink convection based on Theta (sa) of .5 c/w

Trial 1: Current copper heat spreader solution

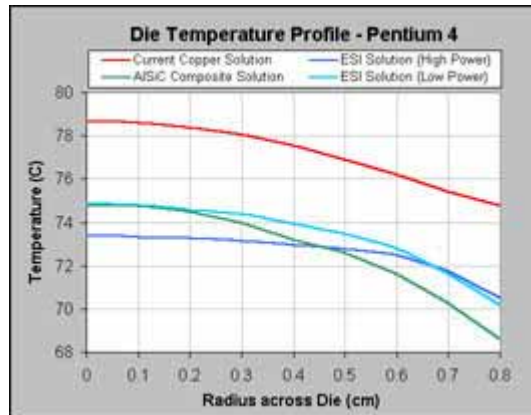
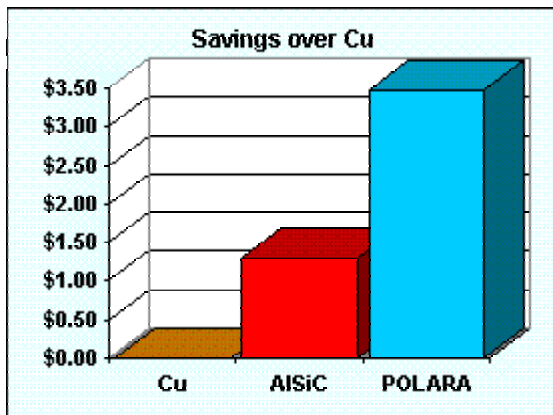
Spreader $k= 4.0$ w/cm-K, Die attach= .01 w/cm-K;

Trial 2: AlSiC composite competitive solution

Spreader $k= 1.8$ w/cm-K, Die attach= .68 w/cm-K;

Trials 3a and Trials 3b: POLARA™ series solution

Spreader $k= 1.20$ w/cm-K, Die attach= .68 w/cm-K,
Peltier wattage= 3a: 10w pumped, 2w consumed; 3b: 5w pumped, 1w consumed



Model 2: AMD Athlon Microprocessor (No Spreader)

Overall Inputs:

Source: 1.1 cm, .05 cm thick, $k=.90$ w/cm-K, **72 Watts**;
Die attach: 1.1 cm, .00254 cm thick, $k=$ (See specific trial inputs)
Heat sink: 7.5 cm, .5 cm thick, $k= 2.0$ w/cm-K.
Heat sink convection based on Theta (sa) of .5 c/w

Trial 1: Current solution (No Spreader)

Die attach= .01 w/cm-K,

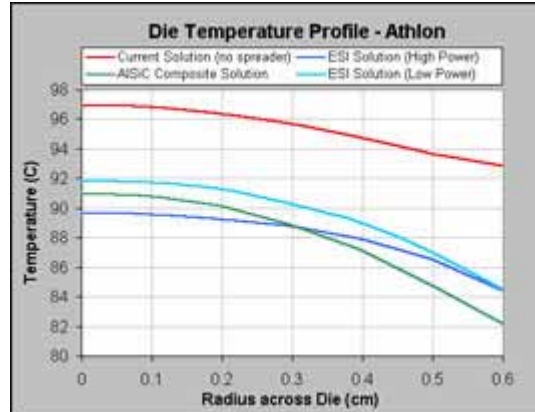
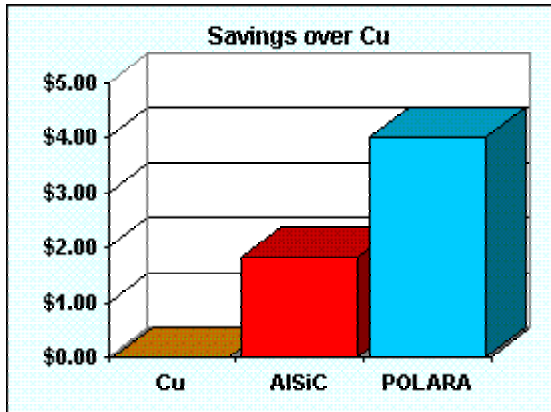
Trial 2: AlSiC composite competitive solution

Spreader k= 1.8 w/cm-K, Die attach= .68 w/cm-K;

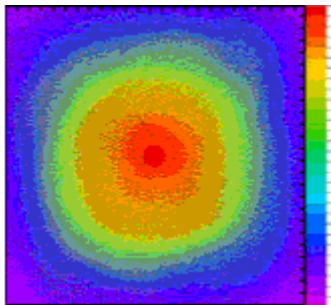
Trials 3a and Trials 3b: POLARA™ series solution

Spreader k= 1.20 w/cm-K, Die attach= .68 w/cm-K,

Peltier wattage= 3a: 10w pumped, 2w consumed; 3b: 5w pumped, 1w consumed



Model 3: Die-Level Thermal Planarization



Overall Inputs:

Source: 1.5 cm, .05 cm thick, k=.90 w/cm-K, **65 Watts**;
Die attach: 1.5 cm, .00254 cm thick, k= (See specific trial inputs)
Spreader: 2.5 cm, .08 cm thick, k= (See specific trial inputs)
Grease: 2.5 cm, .00254 cm thick, k= .01 w/cm-K;O
Heat sink: 7.5 cm, .5 cm thick, k= 2.0 w/cm-K.
Heat sink convection based on Theta (sa) of .5 c/w

Trial 1: Current copper heat spreader solution

Spreader k= 4.0 w/cm-K, Die attach= .01 w/cm-K;

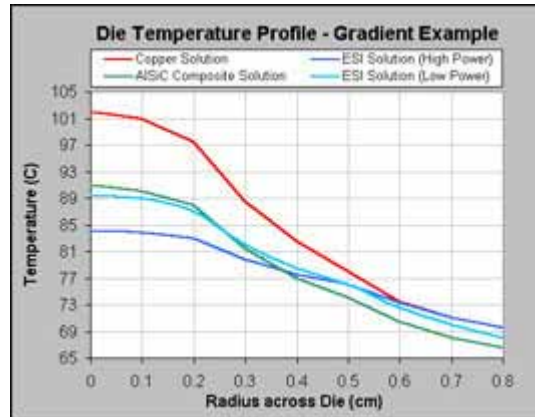
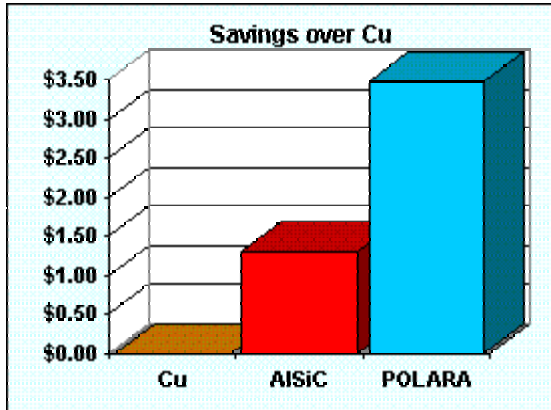
Trial 2: AlSiC composite competitive solution

Spreader k= 1.8 w/cm-K, Die attach= .68 w/cm-K;

Trials 3a and Trials 3b: POLARA™ series solution

Spreader k= 1.20 w/cm-K, Die attach= .68 w/cm-K,

Peltier wattage= 3a: 15w pumped, 3w consumed; 3b: 7.5w pumped, 1.5w consumed



Model 4: Amkor SuperBGA package

Overall Inputs:

Source: 1.0 cm, .05 cm thick, $k=.90$ w/cm-K, **20 Watts**;
 Die attach: 1.0 cm, .00254 cm thick, $k=$ (See specific trial inputs)
 Spreader: 3.5 cm, .08 cm thick, $k=$ (See specific trial inputs)
 Grease: 3.5 cm, .00254 cm thick, $k= .01$ w/cm-K;
 Heat sink: 7.5 cm, .5 cm thick, $k= 2.0$ w/cm-K.
 Heat sink convection based on Theta (sa) of 2.5 c/w

Trial 1: Current copper heat spreader solution

Spreader $k= 2.6$ w/cm-K, Die attach= .01 w/cm-K;

Trial 2: AISiC composite competitive solution

Spreader $k= 1.8$ w/cm-K, Die attach= .68 w/cm-K;

Trial 3: POLARA™ series solution

Spreader $k= 1.20$ w/cm-K, Die attach= .68 w/cm-K,
 Peltier wattage= 5w pumped, 1w consumed

