K-Factor Test-Board Design Impact on Thermal-Impedance Measurements

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SCAA022A
March 1996

Texas Instruments

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Contents

Title *Page*

Abstract

The rapid advancement in semiconductor-device technology is placing unprecedented demands on device-packaging technology. In an effort to meet system requirements for increased speed in smaller footprints, integrated circuit manufacturers are pushing existing packaging technology to new limits. Product performance is a function of both device and packaging technologies. In many instances, the thermal limitations of the packaging system can severely restrict the performance of the device, thus limiting systems applications. System designers and integrated circuit manufacturers are becoming increasingly more concerned about accurate thermal characterization.

There are several indices typically reported to reflect the thermal performance of a package. Thermal impedances, Θ_{JA} (junction to ambient) and Θ_{JC} (junction to case) are the most frequently used throughout the industry. Although there are several specifications on the administration of these tests and measurements, there is no universally accepted industry-wide standard. This lack of standardization promotes an apples-to-oranges comparison of published data, as well as inaccurate estimation of application performance.

This paper focuses on the impact of the wind-tunnel k-factor test-board design parameters on reported Θ_{JA} results. By employing statistical experimental design techniques and finite element analysis (FEA), equations are derived that can be used to quickly normalize reported Θ_{JA} values under various test-board conditions. These mathematical equations are shown to correlate well with empirical wind-tunnel results. A computer program, THETACAL™, has been developed by Texas Instruments (TI) to assist system designers in understanding and comparing the thermal capabilities of packages sourced from various integrated-circuit manufacturers.

Introduction

The use of statistical design of experiment (DOE) techniques combined with FEA provides the engineering community with valuable tools for forecasting the behavior of a system or process. A natural marriage, the DOE and FEA combination allows the engineer to study a range of boundary conditions for numerous design factors and to analyze the impact and associated response for each factor and interaction within the system. With the use of orthogonal polynomial expansion techniques, experimental results can be effectively transformed into mathematical equations based on the strength of the various factors and associated interactions. These equations are useful for performing what-if analyses on a system or process.

The thermal impedance (k-factor) of a package is defined as the increase in junction temperature above the ambient due to the power dissipated by the device and is measured in degrees Celsius per watt. There are two indices commonly used to describe the thermal characteristics of an integrated-circuit package: Θ_{JA} and Θ_{JC}. Θ_{JC} is the thermal impedance from the integrated-circuit die junction to the package external case and is typically measured in a circulating bath of an inert liquid simulating an infinite heat sink. Θ_{JA} is the most widely used and least understood measurement utilized in package selection for application design criteria. There are actually two Θ_{JA} measurements commonly reported:

Socket mounted and measured in 1 cubic foot of still air

Board mounted and measured in a wind tunnel at various air flows

In case #1, the type of socket and socket manufacturer should be noted when comparing reported values, as they can significantly impact the reported Θ_{JA} values.

The focus of this report and the development of the THETACAL software tools are targeted to address the problems associated with board-mounted Θ_{JA} values reported under wind-tunnel conditions (case #2). As indicated earlier, there are several specifications on the administration of wind-tunnel tests and measurements, but there is no universally accepted standard. Wind-tunnel dimensions and k-factor board construction techniques vary widely from manufacturer to manufacturer and can dramatically impact the reported Θ_{JA} values. Figure 1 shows the differences noted on an identical package measured on two

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different integrated-circuit manufacturer’s k-factor boards in the same wind tunnel. In Figure 1, there is roughly a 45°C/W difference (still air) between manufacturers induced by the k-factor board alone. Considering this fact, it is possible for a wide range of reported k-factor values to exist for any given package, depending on the test-board design employed by the manufacturer. Systems designers unaware of these differences can be artificially restricted in packaging selections based only on reported thermal-impedance values.

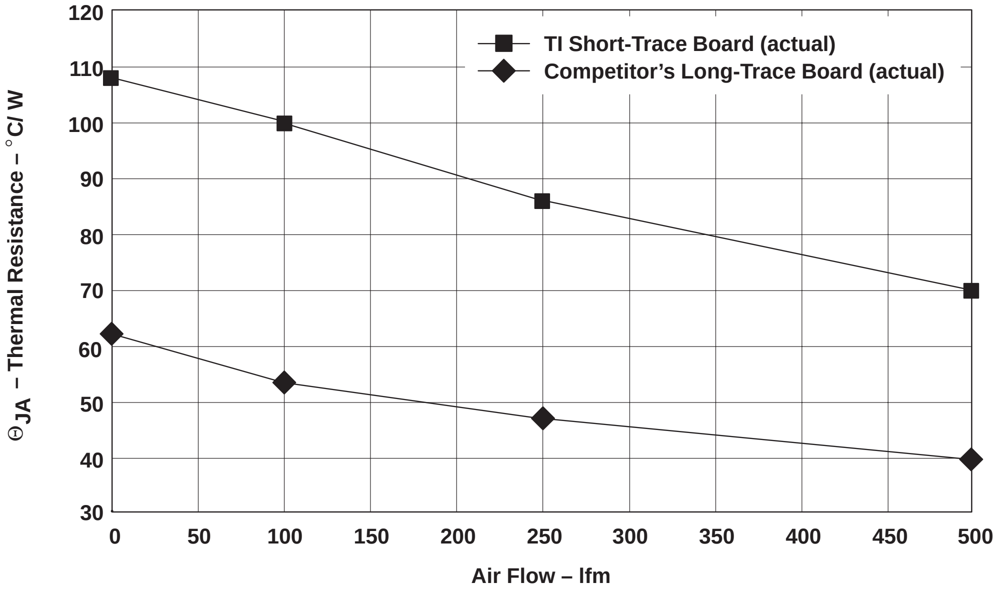

Figure 1. Competitor Versus TI K-Factor Board (52-pin MQFP)

In an effort to provide system designers with an accurate tool for estimating the impact of k-factor test-board designs on reported thermal impedance values (Θ_{JA}), TI has developed the THETACAL software package. By employing statistical experimental design techniques combined with finite element analysis tools, equations can be derived to perform *what-if* analyses varying single or multiple input parameters simultaneously to accurately estimate their impact on the desired response (Θ_{JA}). This tool allows designers to compare the thermal performance of a given package sourced from various manufacturers on an apples-to-apples basis. In addition, the software can be utilized to better understand the influence of the various board-related parameters and their impact on Θ_{JA}.

Modeling Approach

The following four-phase methodology was utilized to develop the THETACAL software package:

1. Design of the experiment using orthogonal arrays
2. Modeling the package using FEA (ABAQUS™) tools
3. Expansion of the matrix results into an orthogonal-polynomial equations
4. Mathematical simulation of the thermal response (Θ_{JA}) for performing what-if analyses

Once the orthogonal-polynomial equations are completed and verified, they are incorporated into the THETACAL software environment. Each package type and pin count are evaluated separately to ensure accuracy in the equations.

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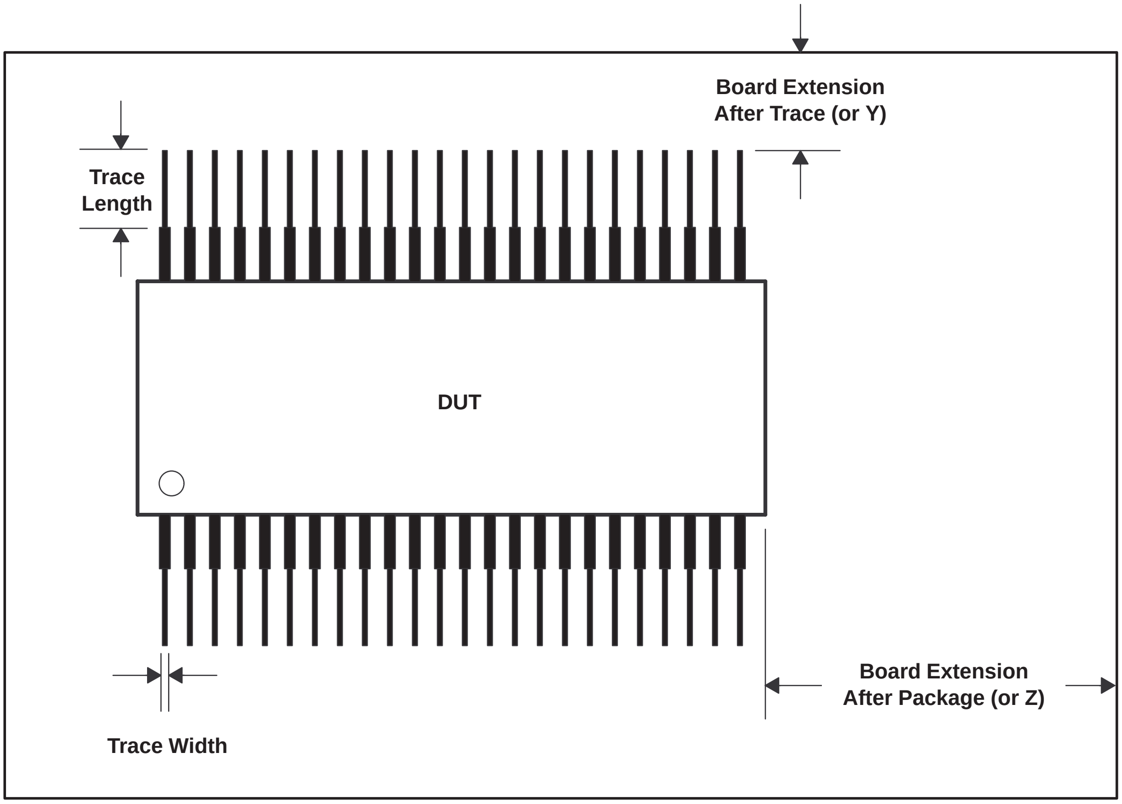
Design of the Experiment

Typical k-factor boards are constructed using an FR4 or polyimide-composite substrate. Copper traces of varying dimensions are fabricated upon this substrate for package mounting and to complete the electrical connections required for k-factor testing. The parameters in Table 1 are most typically varied in k-factor board construction (see Figure 2) and are the focus of this study and the THETACAL software development.

Table 1. Evaluation Parameters

	TRACE LENGTH (mils)	AIR FLOW (lfm)	POWER (watts)	TRACE WIDTH (mils)	BOARD Z EXTENSION (mils)	BOARD Y EXTENSION (mils)	TRACE THICKNESS (mils)
Low	50	0	0.5	3	0	0	1.4
High	750	500	1.5	15	550	550	2.8



NOTE: Y and Z are used for PLCC and QFP packages.

Figure 2. Test Board

An L_{16} orthogonal array[1] was selected as the design vehicle used to evaluate the impact of all identified main factors and their expected interactions within the k-factor test-board system. Since the focus of this study is to derive mathematical equations to be utilized for estimation purposes, it is extremely important to properly define the layout of the experiment to capture all sources of variability; i.e., the accuracy of the equation is best when the unresolved variability is minimized. Once the experiment has been properly defined, appropriate models are prepared per the matrix and processed through the finite element analysis thermal solver (ABAQUS). A typical data set, as returned by the FEA software, is shown in the far right column of Table 2. Statistical analysis is done and orthogonal-polynomial equations can be derived from the completed data set.

Table 2. Matrix Definition and Results

RUN	TRACE LENGTH (mils)	AIR FLOW (lfm)	POWER (watts)	TRACE WIDTH (mils)	BOARD Z EXTENSION (mils)	BOARD Y EXTENSION (mils)	TRACE THICKNESS (mils)	MODEL Θ_{JA} (°C/W)
1	50	0	0.5	3	0	0	1.4	151.3
2	50	0	0.5	15	550	550	2.8	100.6
3	50	0	1.5	3	0	550	2.8	119.2
4	50	0	1.5	15	550	0	1.4	121.2
5	50	500	0.5	3	550	0	2.8	66.5
6	50	500	0.5	15	0	550	1.4	68.6
7	50	500	1.5	3	550	550	1.4	61.6
8	50	500	1.5	15	0	0	2.8	75.5
9	750	0	0.5	3	0	0	2.8	77.7
10	750	0	0.5	15	550	550	1.4	71.6
11	750	0	1.5	3	0	550	1.4	84.0
12	750	0	1.5	15	550	0	2.8	67.5
13	750	500	0.5	3	550	0	1.4	56.1
14	750	500	0.5	15	0	550	2.8	50.0
15	750	500	1.5	3	550	550	2.8	53.5
16	750	500	1.5	15	0	0	1.4	52.5

By using statistical tools such as the effects table (see Table 3) and analysis of variance (ANOVA) table (see Table 4), one can analyze the impact of each individual factor and associated interactions within the system. In Table 4, the air-flow parameter accounts for 47.3% of the total variability measured within the ranges probed, followed closely by the trace length parameter with a 31.4% contribution. In addition, the trace length by air-flow interaction accounts for 8.6% of the variability measured in the system. In total, the airflow, trace length, and the interaction between these two factors accounts for 87.3% of the total variability of the system. The sum of the contribution of the remaining factors is a mere 12.7%. When analyzing the effects table (see Table 3), one can see that employing a longer trace length (see high-level average) on a k-factor board achieves basically the same impact as using a high velocity of moving air across the package. Longer trace lengths on a k-factor board essentially act as built-in heat spreaders on the board and are one of the primary reasons for the dramatic differences noted between manufacturers in reported Θ_{JA} values on identical packages. In light of the fact, it is essential that designers understand the measurement conditions employed when determining the fitness for use of a package for a given application.

Table 3. Effects Table

FACTOR	SUM OF SQUARES	LOW-LEVEL AVERAGE °C/W	HIGH-LEVEL AVERAGE °C/W	EFFECT °C/W
Air flow	5959.84	99.14	60.54	–38.60
Trace length	3956.41	95.56	64.11	–31.45
Trace length by air flow	1079.12	88.05	71.63	–16.42
Board Z ext.	402.00	84.85	74.83	–10.02
Trace length by board Y ext.	304.50	84.20	75.48	–8.72
Trace width	243.36	83.74	75.94	–7.80
Board Y ext.	219.04	83.54	76.14	–7.40
Trace thickness	198.81	83.36	76.31	–7.05
Trace length by board Z ext.	151.29	82.91	76.76	–6.15
Trace length by trace thickness	40.32	81.43	78.25	–3.18
Trace width by trace thickness	15.60	80.83	78.85	–1.98
Trace length by power	8.41	80.56	79.11	–1.45
Air flow by power	7.84	80.54	79.14	–1.40

Table 4. Analysis of Variance (ANOVA) (50-mil thru 750-mil trace lengths)

FACTOR	DOF	SUM OF SQUARES	MEAN SQUARES	F-TEST	% CONTRIBUTION	STATISTICAL SIGNIFICANCE
Air flow	1	5959.84	5959.84	2995	47.3	99%
Trace length	1	3956.41	3956.41	1988	31.4	99%
Trace length by airflow	1	1079.12	1079.12	542	8.6	99%
Board Z ext.	1	402.00	402.00	202	3.2	99%
Trace length by board Y ext.	1	304.50	304.50	153	2.4	99%
Trace width	1	243.36	243.36	122	1.9	99%
Board Y ext.	1	219.04	219.04	110	1.7	99%
Trace thickness	1	198.81	198.81	100	1.6	99%
Trace length by board Z ext.	1	151.29	151.29	76	1.2	95%
Trace length by trace thickness	1	40.32	40.32	20	0.3	95%
Trace width by trace thickness	1	15.60	15.60	8	0.1	
Trace length by power	1	8.41	8.41	4	0.1	
Air flow by power	1	7.84	7.84	4		
Error pool:						
Power	1	3.42				
Trace length by trace width	1	0.56				
Residual		0.005				
Total residual	2	3.98	1.99		0.2	
Total	15	12590.54			100	

Orthogonal-Polynomial Expansion

The results of an orthogonal array can be easily expanded into a powerful orthogonal-polynomial equation. Employing statistical principles, it is possible to construct an accurate mathematical model to quickly estimate the thermal response of a package by analyzing the impact of critical design parameters and key interactions. There has long been a need for an effective thermal calculator that can accurately and reliably estimate the thermal condition of a package under various design parameters, i.e., to analyze the impact of various material, dimensional, and air-flow conditions. Orthogonal-polynomial equations provide such a tool. Utilizing this approach, the solving power of the FEA software can be effectively transformed into a mathematical equation or a system of equations for the desired response for performing what-if analyses within the ranges probed. The general equation format for a two-level orthogonal array with interactions follows. Higher-order equations for nonlinear responses, not described in this work, can also be employed using this technique[2].

General Equation Format

$$\hat{\theta}_{JA} = \overline{\theta_{JA}}$$

$$+ b_{1(a)}(a - \bar{a}) \qquad \text{[linear terms for factor a]}$$

$$+ b_{1(b)}(b - \bar{b}) \qquad \text{[linear terms for factor b]}$$

$$+ b_{11(a - x - b)}(a - \bar{a})(b - \bar{b})\cdots \qquad \text{[interaction terms for factor a – x –b]}$$

Where:

$\hat{\theta}_{JA}$ = Predicted matrix response
$\overline{\theta_{JA}}$ = Average matrix response
$b_{1(i)}$ = Coefficient of the linear response for i
$lvl_{(i)}$ = Number of factor levels at indicated setting for factor i
$h_{(i)}$ = Δ setting between factor levels
$b_{11(i)}$ = Coefficient of interaction response for i
a = Factor input variable for what-if analysis
$\bar{a}$ = Average of factor settings

Factor Coefficients

- **Linear coefficient:**

$$b_{1(a)} = \frac{-A_1 + A_2}{r * \lambda s_{(a)} h_{(a)}}$$

Where:

A_i = Sum of factor response at level indicated
r = Number of runs per factor level
λs = (1 for a 2-level factor) (2 for a 3-level factor)
$h_{(a)}$ = Factor Δ setting

- **Interaction coefficient:**

$$b_{11(A-x-B)} = \frac{[(A_1 + B_1) - (A_1 + B_2)] - [(A_2 + B_1) - (A_2 + B_2)]}{r * \lambda s_A h_A * \lambda s_B h_B}$$

Once the equation is derived, the initial test conditions can be plugged into the equation to check for accuracy against the original modeled parameters as shown in Table 5. If the experiment has been properly designed to capture all significant sources of variability, the equation results should closely match the modeled results. If the error term is minimal (see Table 4), as in this case, the equation matches the modeled results exactly. As the error increases, the accuracy of the equation decreases. At this point, the power of the FEA is transformed into a simple mathematical model for this response within the ranges probed for all parameters. It is now possible to vary individual or multiple input parameters (within the ranges studied) for performing what-if analyses. As with any simulation, equation results should be tested against empirical results to ensure proper accuracy. If the desired accuracy is not achieved, the input models should be reevaluated and adjusted as required.

Table 5. Equation Versus Model

RUN	TRACE LENGTH (mils)	AIR FLOW (lfm)	POWER (watts)	TRACE WIDTH (mils)	BOARD Z EXTENSION (mils)	BOARD Y EXTENSION (mils)	TRACE THICKNESS (mils)	MODEL Θ_{JA} (°C/ W)	EQUATION Θ_{JA} (°C/ W)
1	50	0	0.5	3	0	0	1.4	151.3	151.3
2	50	0	0.5	15	550	550	2.8	100.6	100.6
3	50	0	1.5	3	0	550	2.8	119.2	119.2
4	50	0	1.5	15	550	0	1.4	121.2	121.2
5	50	500	0.5	3	550	0	2.8	66.5	66.5
6	50	500	0.5	15	0	550	1.4	68.6	68.6
7	50	500	1.5	3	550	550	1.4	61.6	61.6
8	50	500	1.5	15	0	0	2.8	75.5	75.5
9	50	0	0.5	3	0	0	2.8	77.7	77.7
10	750	0	0.5	15	550	550	1.4	71.6	71.6
11	750	0	1.5	3	0	550	1.4	84.0	84.0
12	750	0	1.5	15	550	0	2.8	67.5	67.5
13	750	500	0.5	3	550	0	1.4	56.1	56.1
14	750	500	0.5	15	0	550	2.8	50.0	50.0
15	750	500	1.5	3	550	550	2.8	53.5	53.5
16	750	500	1.5	15	0	0	1.4	52.5	52.5

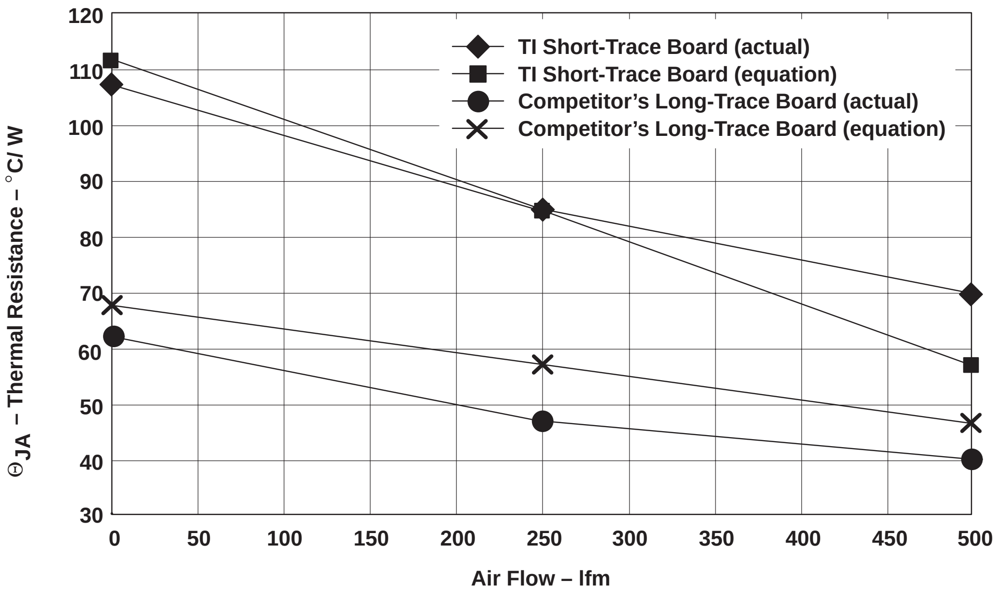


Figure 3. 52-Pin MQFP (actual versus equation)

Verification: Equation Versus Actual Measurements

The air-flow and trace-length parameters were the most dominant influences noted with respect to Θ_{JA}. Wind-tunnel measurements taken on k-factor boards with both short- and long-trace conditions were compared against the orthogonal-polynomial equation. Figure 3 shows that the equation accurately estimates the Θ_{JA} under radically different k-factor board conditions.

Individual FEA-model runs in the orthogonal array used to derive the equation can take several hours of computer processing time, depending on the type of workstation used. In an effort to minimize the modeling time required for each package, 2-level orthogonal arrays were used to minimize the number of runs required to approximate the system. Due to the extremely broad range of trace lengths that can be employed in k-factor test board design (50 mils to 2000 mils), and considering the dramatic influence of the trace-length parameter on Θ_{JA}, two separate matrices are evaluated for each package. The impact on the Θ_{JA} induced by the trace-length parameter is quite dramatic on most packages between 50 mils and 750 mils. From 750 mils to 2000 mils, the impact is less dramatic. In an effort to achieve acceptable equation resolution using linear approximations, two matrices were evaluated for each package. The first matrix focused on the shorter trace lengths and the second matrix focused on the longer traces. In the THETACAL software, this is transparent to the user upon input; however, minor discontinuities may be noted where the equations converge.

The equation(s) can now be utilized to perform what-if analyses on the various input parameters. Figure 4 indicates the impact that the trace length has on Θ_{JA} at various wind-speed conditions.

The knee of the curve at approximately 0.75 inches (750 mils) is the point where the equations from the two matrices converge. The THETACAL software can be used to evaluate any of the parameters considered in the study in a similar fashion. The equations used in the THETACAL software package provide the end users with the power of FEA capabilities (for the Θ_{JA} response) instantaneously and requires no workstation or special skills to use.

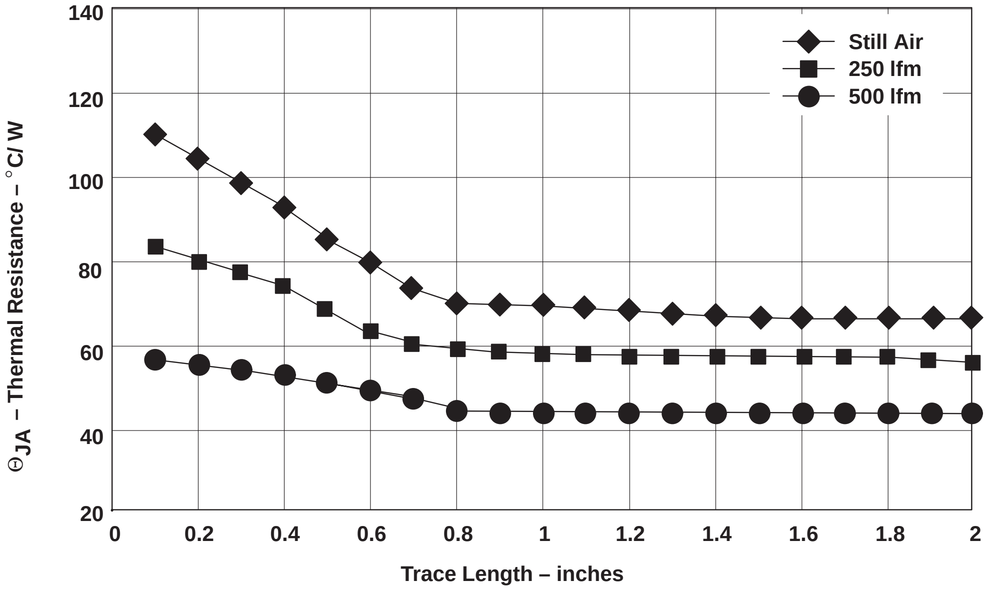


Figure 4. 52-Pin MQFP (trace length effect)

Conclusion

Thermal management of semiconductor packages is becoming increasingly more critical with the move to smaller package geometries and higher power requirements. In order to meet increasingly challenging design goals, systems designers and end users of integrated-circuit packages must be able to make informed decisions on the fitness for use of a package based on thermal considerations. K-factor test-board construction can dramatically impact reported Θ_{JA} results and promote restrictions in package selection and system-performance specifications. The THETACAL software package provides users with an effective tool to normalize reported Θ_{JA} values and assist in making informed decisions on package selection to reach design goals.

Acknowledgements

The author wishes to thank the following persons for their contributions to this work: Paul Noel for his extensive efforts in developing the THETACAL software environment, Dr. Jerald Parker, Professor Jim Cutbirth, and the team of engineering students at Oklahoma Christian University of Science and Arts for their efforts in performing the thermal simulations, and Jim Fielding of Texas Instruments for his extensive modeling efforts. In addition, the author would like to thank Darvin Edwards, Steve Groothius, and Lon McKinstry of Texas Instruments for their support in the areas of finite element analysis and k-factor measurement.

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