Thermal Modeling and Analysis of Device-Contactor-Load Board System

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Abstract – The temperature behavior and heat dissipating capability of a device under test (DUT) in a DUT-contactor-load board test setup is modeled and analyzed to determine the final junction temperature of the die, if it is operating within safe thermal limits and if the setup can dissipate the amount of heat generated while operating under a steady-state condition. A closed form solution and set of equations are presented and used for the purpose of providing a set of guidelines for the test setup. The limiting conditions are few, but the assumption and practice is that the maximum amount of thermal power that can be safely dissipated, without auxiliary cooling, is less than four (4) watts. This is predicated on the design and application of copper inserts in the contactors to conduct heat away to the surrounding environment.

I. INTRODUCTION

As IC devices become ever smaller and electrical power requirements increase, the problem of removing heat from the DUT takes on an increasing importance, especially in test setups on a production floor. In a test environment, the devices cannot be soldered to the load board. Instead they are inserted, one-at-a-time, into a contactor and rely solely upon mechanical pressure to make electrical and thermal contact. However the presence of a contactor causes performance degradation to the overall test system. Under these circumstances, novel solutions must be imposed including knowledge of the electrical and thermal resistance at the interface surfaces which must be considered and analyzed.

It is not unusual for a DUT in an automated test setup to undergo test cycles from a few milliseconds to upwards of a few minutes. In characterization testing, when the device is mounted in a bench setup, the testing in steady-state (SS) conditions may continue for many minutes. This means the DUT must be capable of operating safely in the setup, that the final temperature of the die is within limits and that the setup can safely dissipate heat loads of several watts…if necessary. It is in this vein that heat and current issues are addressed and a way of calculating them is available. This can be done with a fair degree of accuracy and assurance. The methodology presented herein will provide guidance on how this is done from the die in the DUT to the load board-ambient environmental interface. It is not the purpose of these guidelines to address the measure of auxiliary cooling, but the end results will certainly determine if extra cooling is necessary. In this case, the reader is advised to consult several of the many excellent texts on this matter such as Remsburg [1] and Kraus [2].

II. ANALYSES

The methodology of analysis employed can be divided into several steps. Initially, the analyst would create a schematic model of the device and test setup. The model should clearly show all elements that must be analyzed. Information regarding the DUT can generally be taken directly from the manufacturer’s data sheets and should include the DC input power, efficiency, power out, and thermal resistance, junction-to-case. One must also study the geometry and metrics of the device package, especially those pertaining to the thermal ground pad. It is also essential that the plating material on the lands or pads of the device be noted since this directly affects the thermal and electrical resistances of the DUT-to-contact interface. The most common plating materials in use today are matte tin, nickel-palladium-gold, or nickel-palladium. These are plated over high-strength beryllium-copper leadframes to give good conductivity and rigidity to the device.

A normal thermal model in common use is the two-resistor one proposed by Andrews [3]. In 90% to 95% of most cases, any heat generated will exit the device via conduction through the thermal ground pad on the bottom of the device package. Convective heat transfer is usually limited to the loadboard-ambient air environment interface and transfer by emission or radiation is virtually non-existent. This explains why it is absolutely mandatory to have a highly conductive thermal ground insert in the floor of the contactor and that it forms a solid mechanical interface with both the device and the loadboard pads. Anything less will cause high thermal resistance interface connections and could lead to softening of the plating material in certain instances where high current is involved. If this condition could occur, it is worthwhile to apply Ohm's law to the interface to obtain the voltage drop and consult a table of softening voltages with the result - Timsit [4].

The analytical procedure will open with a method of calculating the thermal and electrical resistances of a contact in the contactor both from its equivalent form and when employed in the interface position. The methodology will continue in a similar manner to show how the ground insert is characterized with its interface. Finally, the contactor will be depicted in equivalent form and combined with a loadboard to fully characterize the setup. When the overall thermal resistance of the setup has been determined, it can be applied, along with a maximum die temperature to obtain the safely allowable heat dissipation.

Assumptions made for this procedure are…

a) The system is a continuous thermal function
b) Maximum die junction temperature is +150°C
c) Maximum heat dissipation is limited to <4 Watts
d) Temperature is instantaneously isothermal at any cross-section
e) Real contact area at interfaces is ~1/3 apparent area of contact
f) Softer material will yield to harder material when under pressure at an interface
g) While informative, Hertz stress analysis is not a proper indicator of area of contact between two surfaces at an interface

An example will be incorporated to concretely show the power of the methodology described in this paper.

A. *Solution of Thermal and Electrical Resistances of Stand-Alone Contact*

The thermal resistance, R_θ, of a metallic rod (bar) or contact with an equivalent rod-like shape is given by the following equation.

$$R_\theta = L/(\kappa * A) \tag{1}$$

Where

L = length
κ = thermal conductivity of rod material
A = cross-sectional area

Likewise, the electrical resistance of the rod-like equivalent form of the contact is,

$$R_e = (\rho * L)/A \tag{2}$$

Where

L = length
ρ = electrical resistivity of rod material
A = cross-sectional area

The mass of the contact is calculated by using the equation

$$m = (\rho * V) \;\; \text{Kg} \tag{3}$$

Where

ρ = density of the contact material (Kg/m^3)
V = volume of the contact (m^3)

B. *Solution of Thermal Resistance and Heat Transfer Capability of Contact Interfaces*

Heat transfer across a metallic interface is stipulated by determining the heat transfer interface coefficient, h_i. A closed-form useful equation that depicts this relation is given by Cooper [5] and Remsburg [1] and is:

$$h_i = 1.45 * \{[\kappa * (P_a/H)^{0.985}/\sigma]\} * \tan\varphi \quad \text{Watts/m}^2 - \text{K} \qquad (4)$$

Where

$\kappa = 0.5 * \kappa_1 * \kappa_2/(\kappa_1 + \kappa_2)$ and κ_1 and κ_2 are the thermal conductivity of materials 1 and 2 in (W/m-K)
P_a = contact pressure at the thermal interface (N/m^2)
H = hardness of the softer material (N/m^2 x 10^8)
$\sigma = (\sigma_1^2 + \sigma_2^2)^{1/2}$ and σ_1 and σ_2 are the rms roughness of materials 1 and 2 (μm)
$\tan \Phi_1 = 0.125 * (\sigma_1 \times 10^6)^{0.402}$
$\tan \Phi_2 = 0.125 * (\sigma_2 \times 10^6)^{0.402}$
$\tan\Phi = (\tan \Phi_1^2 + \tan \Phi_2^2)^{1/2}$ where Φ_1 and Φ_2 are the absolute asperity angles of materials 1 and 2

However, the heat transfer coefficient, h_i, is only one facet of heat transfer across an interface and applies to the asperites in contact with each other. This area has been investigated and analyzed by Kogut and Komvopoulos [6], et. al. Most of the contact area is a void consisting of valleys between the peaks. These must be accounted for since they form a parallel, albeit less conducting path in the contact area which sums with the paths of "hard conduction." This approach was addressed by Shlykov [7] and is defined by the equation,

$$h_{gi} = k_g/Y = k_g/[(Y/\sigma) * \sigma] \quad \text{Watts/m}^2 - \text{K} \qquad (5)$$

Remsburg [1] posits that the quantity, Y/σ, relates to the surface finishing of the material and is shown in Table 1 as a metric function of the finishing operation.

Table 1. Finishing Operation vs. Values of Y/σ

Finishing Operation	**Y/σ**
Grinding	4.5
Hyperlap	6.5
Sandpaper	7.0
Superfinish	7.0
Lap w/loose abrasive	10.0

The total heat transfer across an interface between two materials is thus the sum of h_i and h_{gi}. By way of explanation, these parameters form a parallel path for heat transfer. In this respect, they are thermal conductance paths and parallel conductances sum directly. The inverse of the product of this value and the apparent area of surface contact, A_a, will give the thermal resistance, θ_a (°C/W), as stipulated in Eq. 5 immediately below.

$$\Theta_a = 1/[(h_i + h_{gi}) * A_a] \qquad (6)$$

Another factor in calculating the thermal resistance of an interface lies in determining the area of contact between the elements. Since the roughness of the surface of each contacting material depends on the nature of said material, and since the softer material will be compacted by the harder one under an applied force, one can create a geometric condition that can be used to estimate the degree of contact. Refer to Fig. 1 and Eq. 7 for an approximation to the solution.

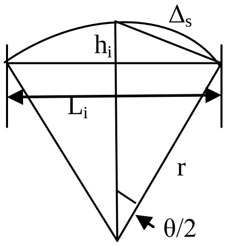

Fig.1. Interface Geometry to Determine Contact Area

$$L_i = 2 * (2*h_i*r - h_i^2)^{1/2} \quad \text{meters} \tag{7}$$

Where

r = radius of contacting surface in meters
h_i = average surface roughness of softer material in meters

It follows that the apparent area of contact is the product of L_i and the width of the contact. There are two interfaces for a DUT in a contactor, namely one between the pads or leads of the device and the contact and the other between the contact and the loadboard pads. Therefore, the overall thermal resistance, $R_{\theta,\text{contact-Ifs}}$, of a contact is given as:

$$R_{\theta,\text{contact-Ifs}} = R_{\theta,\text{contact}} + R_{\theta,\text{IF1}} + R_{\theta,\text{IF2}} \quad °\text{C/W} \tag{8}$$

Where

$R_{\theta,\text{IF1}}$ = thermal resistance of IF1 contact in (°C/W)
$R_{\theta,\text{IF2}}$ = thermal resistance of IF2 contact in (°C/W)

C. *Solution of Thermal Resistance and Heat Transfer Capability of Thermal Ground Insert and its Interfaces*

Heat transfer from the thermal pad of the DUT to the loadboard and thence to the environment is via conduction. From a practical standpoint, the most effective economical material to use is copper which has the second highest thermal conductivity next to silver (the highest). Table 2 lists some typical properties of metals, or in the case of beryllium-copper (alloy), used as wire materials.

Table 2. Typical Properties of Metals

Property	**Copper**	**Gold**	**Beryllium-Copper**
Melting Point, T_m	1,083°C	1063°C	980°C
Thermal Conductivity, κ @ 20°C	394 W/m-K	294 W/m-K	95 W/m-K
Density, ρ	8,950 Kg/m^3	19,300 Kg/m^3	8,321.4 Kg/m^3
Electrical Resistivity, ρ_e @ 20°C	$1.65\text{x}10^{-8}$ Ω-m	$2.19\text{x}10^{-8}$ Ω-m	$7.68\text{x}10^{-8}$ Ω-m
Thermal Coef. Of Resistivity, α	0.0043 1/C	0.0040 1/C	0.0010 1/C
Specific Heat, c_p	385 J/Kg-K	129 J/Kg-K	418.7 J/Kg-K
Electrical Conductivity @ 20°C	$59.9\text{x}10^6$ 1/Ω-m	$45.7\text{x}10^6$ 1/Ω-m	$13.0\text{x}10^6$ 1/Ω-m

The equations shown in Section II, parts A and B of this paper are directly applicable and can be used to solve for the electrical and thermal resistance of the ground insert. The methodology used to determine the contact interface between the DUT thermal pad and the insert and between the insert and the loadboard pads also applies. If contacts are used in the ground insert, then allowance must be made for the volume of material removed, per slot, and for the reduction in contact surface area. The total thermal resistance of the ground insert and its accompanying interfaces is the sum of their numeric values and is…

$$R_{\theta,\text{insert-Ifs}} = R_{\theta,\text{insert}} + R_{\theta,\text{insert-IF1}} + R_{\theta,\text{insert-IF2}} \quad °C/W \tag{9}$$

Where

$R_{\theta,\text{insert-IF1}}$ = thermal resistance of insert-IF1 contact in (°C/W)
$R_{\theta,\text{insert-IF2}}$ = thermal resistance of insert-IF2 contact in (°C/W)

D. *Solution of Thermal Resistance and Heat Transfer Capability of the Contactor with Ground Insert and Contacts*

The thermal resistances of the basic components of a contactor have been addressed. These components must be assembled to give a total thermal resistance for the contactor. Eqs. 10 and 11 define this operation.

$$R_{\theta,\text{ contactor}} = R_{\theta,\text{ housing}} \parallel R_{\theta,\text{ N contacts}} \parallel R_{\theta,\text{ insert+contacts}} \tag{10}$$

$$R_{\theta,\text{ contactor}} = [(1/ R_{\theta,\text{ housing}}) + (N/R_{\theta,\text{ contact}}) + (1/ R_{\theta,\text{ insert+contacts}})]^{-1} \quad °C/W \tag{11}$$

Where

N = number of contacts

E. *Solution of Thermal Resistance and Heat Transfer Capability of DUT-Contactor-Loadboard System*

At this point, it is instructive to depict a schematic model of the DUT-Contactor-Loadboard system in order to clearly enumerate the path of heat transfer to the environment in a test setup. Refer to Fig. 2 for the model. For purposes of simplification, “Rth IF+Pins” includes the peripheral contacts in parallel with the thermal resistance of the insert with its contacts.

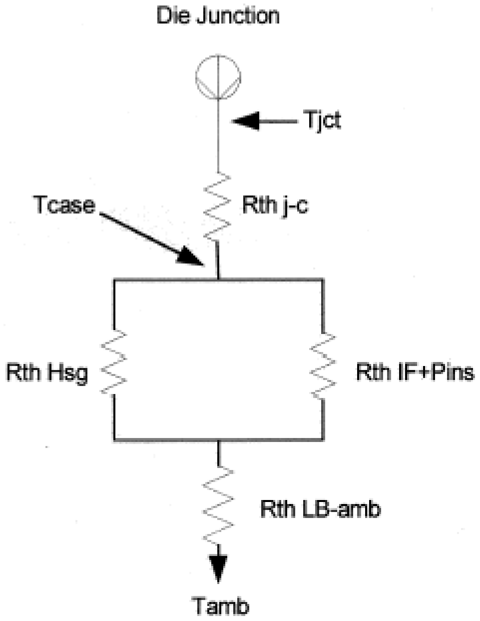

Fig. 2. Schematic Model of Thermal System

Loadboards come in all sizes and more than a few shapes so the issue of how to model one hinges on a specific loadboard related to the system on hand. However one can use a flat plate model for a loadboard with a fair degree of accuracy. The thermal resistance of a flat plate to a first order approximation (±10%) is given by Korzeniowski [8] as,

$$R_\theta = 80 * A^{-0.7} * P^{-0.15} \quad °C/W \tag{12}$$

Where

A = area in square inches (including both sides)
P = power in Watts (heat load)

If the loadboard or printed circuit board is coated with ½ ounce copper (low mass), spreading resistance (lateral resistance to heat flow) becomes a consideration, whereby the heat flow through the copper foil decreases with distance thereby causing radiation to the air, and also the temperature, to decrease measurably with distance from the heat source. In the case of ½ ounce copper, the heat sinking is effectively limited to less than a ½ inch circle. Increasing the thickness of the copper to 1 ounce will increase the heat sinking to the diameter of a 2 inch circle. For high performance, e.g. RF circuit boards, a common practice is to make the upper and lower outer layers of microwave PCB material such as Rogers RT/duroid® 5880. They are glued to interior layers of standard FR-4 material. The latter layers sustain the power and low frequency circuits associated with the DUT. Heat transfer from the loadboard to the environment is by convection with an excellent explanation of this process for loadboards in any orientation given by Remsburg [1] in his text on advanced thermal design.

As mentioned earlier in this paper, the ultimate goal of a test system of the nature described herein is to ensure that the temperature of the die in the DUT in operating within safe limits and that any heat generated is efficiently transferred to the environment. Once the thermal resistance of the system in has been determined and the amount of heat calculated, then it is possible to calculate the final temperature of the die and conversely, if the maximum die temperature is specified, it is possible to determine the maximum power the device can handle. Equations 13 and 14 can be used to calculate the aforementioned factors.

$$\text{Temp. Die} = T_{amb} + (P_{Diss} * R_{\theta,\text{ system}})\ ^{\circ}\text{C} \qquad (13)$$

Where

Temp. Die = the final operating temperature of the die (°C)
T_{amb} = Ambient temperature of the environment (°C)
P_{Diss} = Power dissipated (heat) by the DUT (Watts)
$R_{\theta,\text{ system}}$ = Overall thermal resistance of the system (cf. Fig. 2) (°C/W)

and

$$P_{Diss} = (T_j - T_{amb}) / R_{\theta,\text{ system}}\ \text{(Watts)} \qquad (14)$$

Where

T_j = junction temperature of die (°C), upper limit is generally 150°C

An example of what can be achieved with the processes and methodology that is the subject of this paper is given in Table 3. The genesis of this table was to determine and tabulate the thermal resistance vs. contact count vs. power dissipation of various size QFN packaged devices using two forms, namely,

1. Pad ROL100™ contacts in a Torlon™ housing, and
2. Pad ROL100™ contacts in a copper ground insert in a Torlon™ housing

Pad ROL100™ contacts are a product of Johnstech International Corp., Minneapolis, MN

Assumptions made when creating this table include:

a) Maximum die junction temperature = +150°C
b) Ambient temperature = +25°C
c) Total system thermal resistance = (25 + Factor) °C/W

Table 3. Summary of RTH and RCI Thermal Characteristics
for Pad ROL100™ Contacts and Inserts

Package Size	RTH Grounding # of Contacts	RTH Grounding (°C/Watt)	RTH Grounding Power Diss. (Watts)	RCI Grounding # of Contacts	RCI Grounding (°C/Watt)	RCI Grounding Power Diss. (Watts)
3x3	N/A	N/A	N/A	Insert Only (CI)	33.07	3.78
5x5	5 Contacts (RTH)	46.6	2.68	3 Contacts (RCI)	30.47	4.10
7x7	12 Contacts (RTH)	34.8	3.59	12 Contacts (RCI)	29.73	4.35
9x9	12 Contacts (RTH)	34.8	3.59	12 Contacts (RCI)	28.33	4.41

III. Example of a Case Study

A. *Example of Thermal Resistance and Heat Transfer Capability of DUT-Contactor-Loadboard System*

As with many theoretical studies, it is always instructive to include an illustrative example to highlight the use of the equations and material involved. In this case one is asked to determine the thermal dissipation capability of a 1mm contactor with an 8- QFN 5X5 package footprint for the DUT. The DUT is a Ka – Band, Microwave Power Amplifier with an RF output of 1 Watt and a DC input power of 5 Watts. A list of specifications and parameters for this device and setup is shown immediately below.

- Contactor is a Pad Series ROL100™ product
- Three ROL100™ contacts in a copper insert for ground/thermal
- Eight ROL100™ peripheral contacts
- Plating material on DUT pads is matte tin
- Test Temperature Range: Ambient (+25°C)
- Operating Voltage (for each device): +5.0 VDC
- Input current: 1000 MA DC
- Power (Watts) of each device: 5 W DC
- RF output power: 1 Watt
- DC-to-RF conversion efficiency: ~20%
- Energy dissipated as heat: ~4 Watts
- Test Time Duration: > 1 minute
- Duty Cycle: Steady-State (100%)
- Possible topology of PCB
  - 2 Layers with the top layer dedicated to ground
  - FR-4 PCB’s are 4.5” x 4.5” x 0.010” thick
  - Copper traces are ½ ounce with 50 µinches of gold over 200 µinches nickel

B. *Solution and General Calculations*

This analysis is based on a Pad ROL100™ contactor with a 2.6mm x 2.8mm copper insert having three (3) ROL100™ BeCu contacts, 0.254mm wide inserted therein. Additionally, there will be a total of eight (8) similar contacts around the periphery of the contactor for additional heat transfer to the load board and the environment. The 1mm, 0.254mm (0.010”) wide ROL100™ contact is fabricated from a beryllium-copper alloy (98%Cu, 2%Be) and has the following characteristics. Refer to Table 2 for the properties of beryllium-copper alloy.

Applying the formulas Section II, parts A through F and using the numerics listed above, one can formulate a list of values as shown in Table 4. With respect to convective heat transfer from the loadboard-to-ambient air environment, an excellent explanation of this phenomenon is given by Remsburg [9] using the technique of circular fin analysis involving real and imaginary Bessel functions.

Table 4. Calculated Values for Test System

Parameter	**Numerical Value and Units**
Cross-sectional area of contact	$8.87\text{x}10^{-8}$ m^2
Thermal resistance of contact	114.3°C/W
Applied force at DUT-contact IF1	0.637 Newton
Apparent area of contact at DUT-contact IF1	$7.97\text{x}10^{-9}$ m^2
Thermal resistance of IF1	2.1°C/W
Applied force at contact-LB IF2	0.539 Newton
Apparent area of contact at contact-LB IF2	$1.39\text{x}10^{-8}$ m^2
Thermal resistance of IF2	9.9°C/W
Thermal resistance of Contact-IF1-IF2	126.3°C/W
Thermal resistance of copper insert w/3 contacts	4.5°C/W
Thermal resistance of contactor w/contacts+insert	4.4°C/W
Thermal resistance of load board	15.0°C/W

C. *Results*

Now consider the temperature of a die within the 8-QFN device at ambient temperature under the following conditions.

- Heat load (Q): = 4.0 Watts
- θ_{jc} = 6.5°C/W Estimated
- R_θ = 25.9°C/W
- Test time: > 1 minute

The overall thermal impedance from the die in the device to ambient air is,

$$\theta_T = \{\theta_{jc} + (\theta_{Total}) + \theta_{pcb\text{-}a}\}°C/W \tag{15}$$

thus,

$$\theta_T = 6.5 + 4.4 + 15.0 = 25.9°C/W$$

What is the expected temperature of a die within the device?

$$@T_A \text{ of } +25°C: \quad T_D = +25 + (4.0 \text{ x } 25.9) = +128.6°C$$

The maximum operating temperature of the die within the device, depending upon the substrate base is +175°C for silicon and +150°C for Gallium-Arsenide. For purposes of this example, it is assumed that the die temperature must not exceed +150°C, maximum. Normally, one would want a buffer zone, hence the temperature of the die should not exceed +130°C for any length of time. Another factor to consider is that the allowable safe operating limit for FR-4 material is ~130°C, whereas the 5880 material can safely function at temperatures up to 250ºC. This condition is being met at ambient temperatures of +25°C, and a 100% duty cycle for the case depicted in this example.

IV. Conclusions

A thermal system and test setup involves a reasonable amount of preliminary thought and work to ensure that safe operating limits of the DUT are maintained. It is possible to calculate the estimated die junction temperature and maximum allowable heat dissipation for such a setup by using the methodology, equations, tables and guidelines set forth in this document. A case study was used as an example to illustrate the processes. In the example, the amount of heat dissipated by 5x5 QFN package device is calculated to be 4 Watts. According to the information shown in Table 3, a package of this size should be able to safely dissipate 4.1 Watts with a copper ground insert and three contacts. A comparison between this value and results of the example shows excellent agreement. This has also been verified by laboratory testing using a similar test setup with a 7x7 device package an equivalent overall thermal resistance.

NOMENCLATURE

▪ Heat flux	J/m^2-s
▪ Heat transfer rate	$dQ = qA(W/m^2)$
▪ Mass density, ρ	Kg/m^3
▪ Specific heat, c_p	J/Kg-k
▪ Thermal conductivity, k	W/m-k
▪ Thermal energy	Q(Joules)
▪ Thermal resistance, θ	°C/W
▪ Thermal time constant, γ	sec

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