AN569/D

Transient Thermal Resistance - General Data and Its Use

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APPLICATION NOTE

Prepared by: Bill Roehr and Bryce Shiner
ON Semiconductor
Applications Engineering

Introduction

For a certain amount of dc power dissipated in a semiconductor, the junction temperature reaches a value which is determined by the thermal conductivity from the junction (where the power is dissipated) to the air or heat sink. When the amount of heat generated in the junction equals the heat conducted away, a steady–state condition is reached and the junction temperature can be calculated by the simple equation:

$$T_J = P_D R_{\theta JR} + T_R \quad (1a)$$

where:

T_J = junction temperature;
T_R = temperature at reference point;
P_D = power dissipated in the junction;
$R_{\theta JR}$ = steady–state thermal resistance from junction to the temperature reference point.

Power ratings of semiconductors are based upon steady–state conditions, and are determined from equation (1a) under worst case conditions, i.e.:

$$P_{D(max)} = \frac{T_{J(max)} - T_R}{R_{\theta JR(max)}} \quad (1b)$$

$T_{J(max)}$ is normally based upon results of an operating life test or serious degradation with temperature of an important device characteristic. T_R is usually taken as 25°C, and $R_{\theta JR}$ can be measured using various techniques. The reference point may be the semiconductor case, a lead, or the ambient air, whichever is most appropriate. Should the reference temperature in a given application exceed the reference temperature of the specification, P_D must be correspondingly reduced.

Equation (1b) does not exclusively define the maximum power that a transistor may handle. At high power levels, particularly at high voltages, second breakdown may occur at power levels less than that given by equation (1b). (Second breakdown is a result of current concentrating in a small area which causes the transistor to lose its ability to sustain a collector–emitter voltage. The voltage drops to a low value generally causing the circuit to deliver a very high current to the transistor resulting in a collector to emitter short.) Second breakdown can be prevented by operating within the Safe Area given on a manufacturer's data sheet. Needless to say, abiding by the Safe Area is most important in avoiding a catastrophic failure.

DC Safe Area and the thermal resistance allow the designer to determine power dissipation under steady–state conditions. Steady–state conditions between junction and case are generally achieved in one to ten seconds while minutes may be required for junction to ambient temperature to become stable. However, for pulses in the microsecond and millisecond region, the use of steady–state values will not yield true power capability because the thermal response of the system has not been taken into account.

Note, however, that semiconductors also have pulse power limitations which may be considerably lower – or even greater – than the allowable power as deduced from thermal response information. For transistors, the second breakdown portion of the pulsed safe operating area defines power limits while surge current or power ratings are given for diodes and thyristors. These additional ratings must be used in conjunction with the thermal response to determine power handling capability.

To account for thermal capacity, a time dependent factor r(t) is applied to the steady–state thermal resistance. Thermal resistance, at a given time, is called transient thermal resistance and is given by:

$$R_{\theta JR(t)} = r(t) \cdot R_{\theta JR} \quad (2)$$

The mathematical expression for the transient thermal resistance has been determined to be extremely complex. The response is, therefore, plotted from empirical data. Curves, typical of the results obtained, are shown in Figure 1. These curves show the relative thermal response of the junction, referenced to the case, resulting from a step function change in power. Observe that during the fast part of the response, the slope is 1/2 for most of the devices; (i.e., $T_J \propto \sqrt{t}$), a characteristic generally found true of metal package devices. The curves shown are for a variety of transistor types ranging from rather small devices in TO–5 packages to a large 10 ampere transistor in a TO–3 package. Observe that the total percentage difference is about 10:1 in the short pulse ($\sqrt{t}$) region. However, the values of thermal resistance vary over 20:1. As an aid to estimating response, Appendix C provides data for a number of packages having different die areas.

Many ON Semiconductor data sheets have a graph similar to that of Figure 2. It shows not only the thermal response to a step change in power (the D = 0, or single pulse curve) but also has other curves which may be used to obtain an effective r(t) value for a train of repetitive pulses with different duty cycles. The mechanics of using the curves to find T_J at the end of the first pulse in the train, or to find $T_{J(pk)}$ once steady–state conditions have been achieved, are quire simple and require no background in the subject. However, problems where the applied power pulses are either not identical in amplitude or width, or the duty cycle is not constant, require a more thorough understanding of the principles illustrated in the body of this report.

Use of Transient Thermal Resistance Data

Part of the problem in applying thermal response data stems from the fact that power pulses are seldom rectangular, therefore to use the r(t) curves, an equivalent rectangular model of the actual power pulse must be determined. Methods of doing this are described near the end of this note.

Before considering the subject matter in detail, an example will be given to show the use of the thermal response data sheet curves. Figure 2 is a representative graph which applies to a 2N5632 transistor.

Pulse power, P_D = 50 Watts
Duration, t = 5 milliseconds
Period, τ_p = 20 milliseconds
Case temperature, T_C = 75°C
Junction to case thermal resistance, $R_{\theta JC}$ = 1.17°C/W

The temperature is desired, a) at the end of the first pulse b) at the end of a pulse under steady–state conditions.

For part (a) use:

$$T_J = r(5\ ms)R_{\theta JC}P_D + T_C$$

The term r(5 ms) is read directly from the graph of Figure 2 using the D = 0 curve,

$$\therefore T_J = 0.49 \times 1.17 \times 50 + 75 = 28.5 + 75 = 103.5$$

The peak junction temperature rise under steady conditions is found by:

$$T_J = r(t, D)R_{\theta JC}P_D + T_C$$

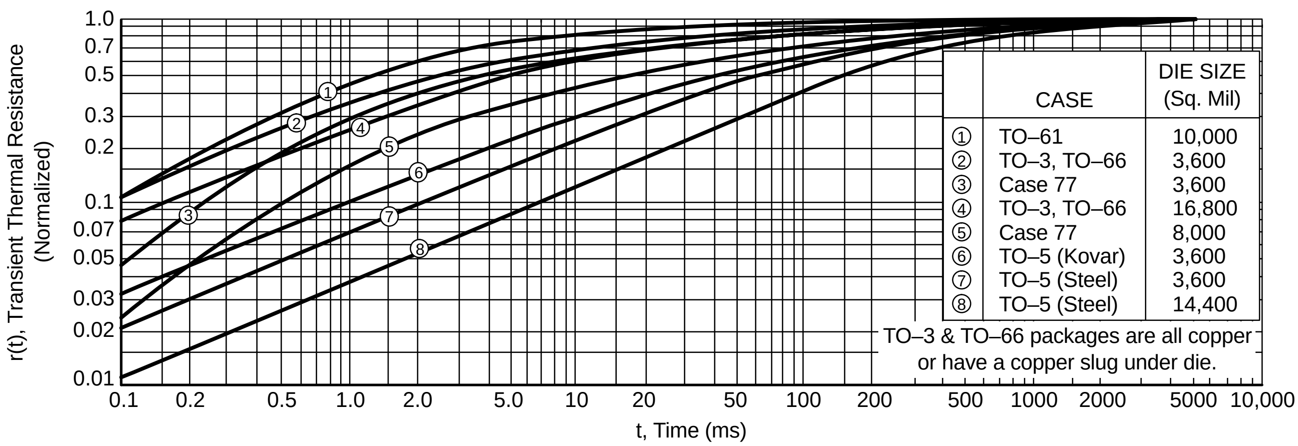

Figure 1. Thermal Response, Junction to Case, of Various Semiconductor Types for a Step of Input Power

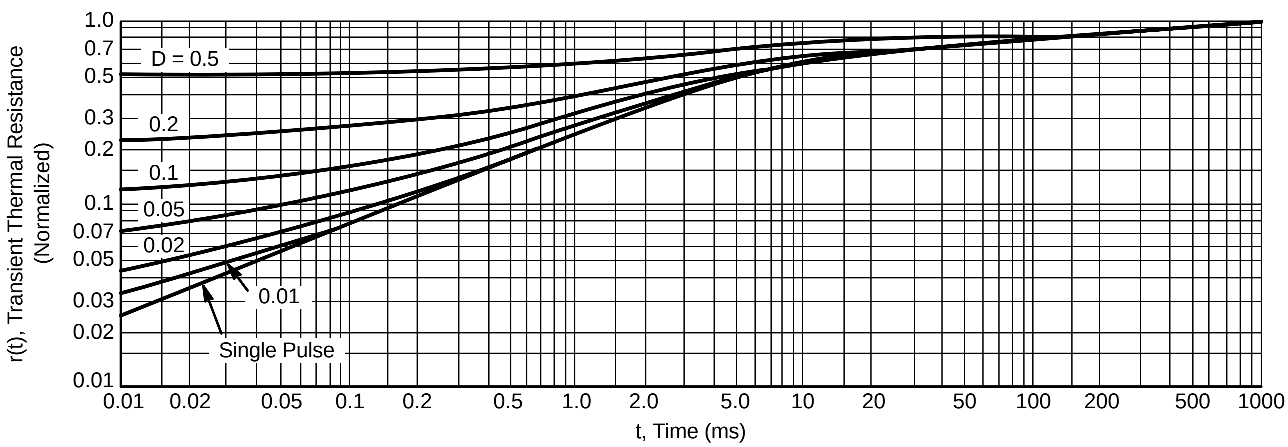

Figure 2. Thermal Response Showing the Duty Cycle Family of Curves

$D = t/\tau_p = 5/20 = 0.25$. A curve for D = 0.25 is not on the graph; however, values for this duty cycle can be interpolated between the D = 0.2 and D = 0.5 curves. At 5 ms, read r(t) ≈ 0.59.

$$T_J = 0.59 \times 1.17 \times 50 + 75 = 34.5 + 75 = 109.5^\circ C$$

The average junction temperature increase above ambient is:

$$\begin{aligned} T_{J(average)} - T_C &= R_{\theta JC} P_D D \\ &= (1.17)(50)(0.25) \\ &= 14.62^\circ C \end{aligned} \tag{3}$$

Note that T_J at the end of any power pulse does not equal the sum of the average temperature rise (14.62°C in the example) and that due to one pulse (28.5°C in example), because cooling occurs between the power pulses.

While junction temperature can be easily calculated for a steady pulse train where all pulses are of the same amplitude and pulse duration as shown in the previous example, a simple equation for arbitrary pulse trains with random variations is impossible to derive. However, since the heating and cooling response of a semiconductor is essentially the same, the superposition principle may be used to solve problems which otherwise defy solution.

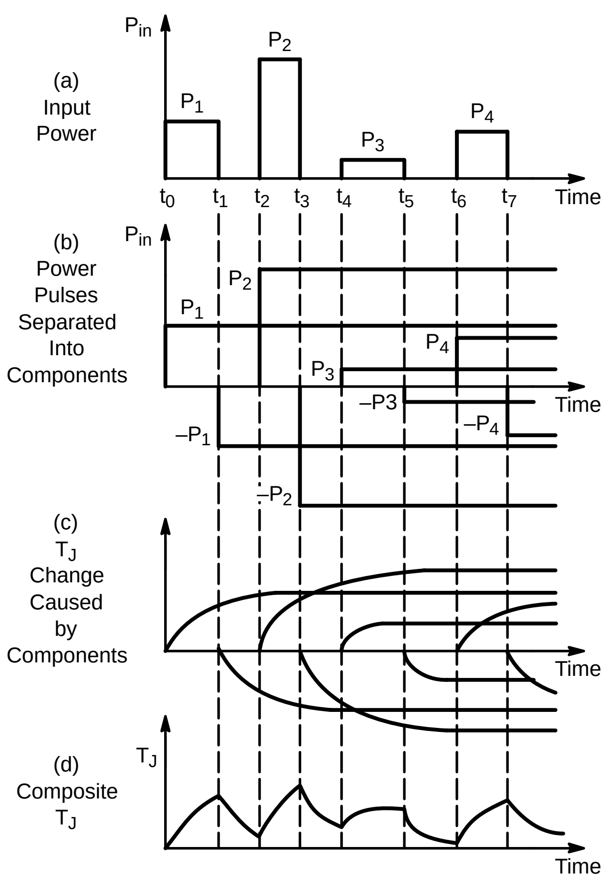

Figure 3. Application of Superposition Principle

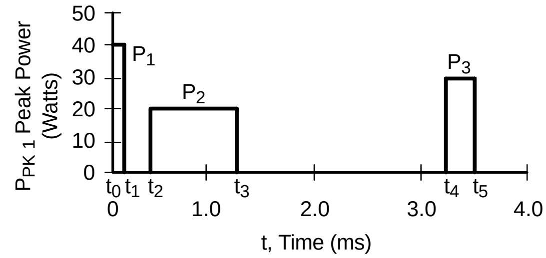

Figure 4. Non–Repetitive Pulse Train (Values Shown Apply to Example in Appendix I)

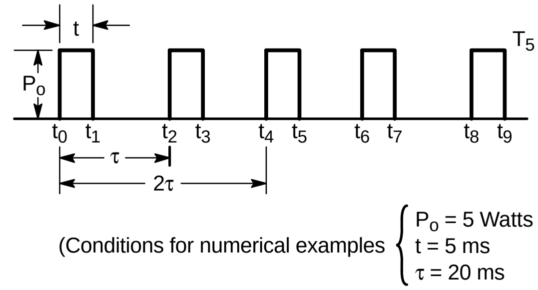

Figure 5. A Train of Equal Repetitive Pulses

Using the principle of superposition each power interval is considered positive in value, and each cooling interval negative, lasting from time of application to infinity. By multiplying the thermal resistance at a particular time by the magnitude of the power pulse applied, the magnitude of the junction temperature change at a particular time can be obtained. The net junction temperature is the algebraic sum of the terms.

The application of the superposition principle is most easily seen by studying Figure 3.

Figure 3a illustrates the applied power pulses. Figure 3b shows these pulses transformed into pulses lasting from time of application and extending to infinity; at t_o, P_1 starts and extends to infinity; at t_1, a pulse ($-P_1$) is considered to be present and thereby cancels P_1 from time t_1, and so forth with the other pulses. The junction temperature changes due to these imagined positive and negative pulses are shown in Figure 3c. The actual junction temperature is the algebraic sum as shown in Figure 3d.

Problems may be solved by applying the superposition principle exactly as described; the technique is referred to as Method 1, the pulse–by–pulse method. It yields satisfactory results when the total time of interest is much less than the time required to achieve steady–state conditions, and must be used when an uncertainty exists in a random pulse train as to which pulse will cause the highest temperature. Examples using this method are given in Appendix A under Method 1.

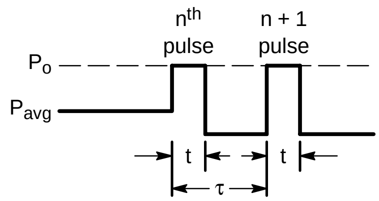

Figure 6. Model for a Repetitive Equal Pulse Train

For uniform trains of repetitive pulses, better answers result and less work is required by averaging the power pulses to achieve an average power pulse; the temperature is calculated at the end of one or two pulses following the average power pulse. The essence of this method is shown in Figure 6. The duty cycle family of curves shown in Figure 2 and used to solve the example problem is based on this method; however, the curves may only be used for a uniform train after steady–state conditions are achieved. Method 2 in Appendix A shows equations for calculating the temperature at the end of the n_{th} or n + 1 pulse in a uniform train. Where a duty cycle family of curves is available, or course, there is no need to use this method.

Temperature rise at the end of a pulse in a uniform train before steady–state conditions are achieved is handled by Method 3 (a or b) in the Appendix. The method is basically the same as for Method 2, except the average power is modified by the transient thermal resistance factor at the time when the average power pulse ends.

A random pulse train is handled by averaging the pulses applied prior to situations suspected of causing high peak temperatures and then calculating junction temperature at the end of the n_{th} or n + 1 pulse. Part c of Method 3 shows an example of solving for temperature at the end of the third pulse in a three pulse burst.

Handling Non–Rectangular Pulses

The thermal response curves, Figure 1, are based on a step change of power; the response will not be the same for other waveforms. Thus far in this treatment we have assumed a rectangular shaped pulse. It would be desirable to be able to obtain the response for any arbitrary waveform, but the mathematical solution is extremely unwieldy. The simplest approach is to make a suitable equivalent rectangular model of the actual power pulse and use the given thermal response curves; the primary rule to observe is that the energy of the actual power pulse and the model are equal.

Experience with various modeling techniques has led to the following guidelines:

- For a pulse that is nearly rectangular, a pulse model having an amplitude equal to the peak of the actual pulse, with the width adjusted so the energies are equal, is a conservative model. (See Figure 7a).
- Sine wave and triangular power pulses model well with the amplitude set at 70% of the peak and the width adjusted to 91% and 71%, respectively, of the baseline width (as shown in Figure 7b).

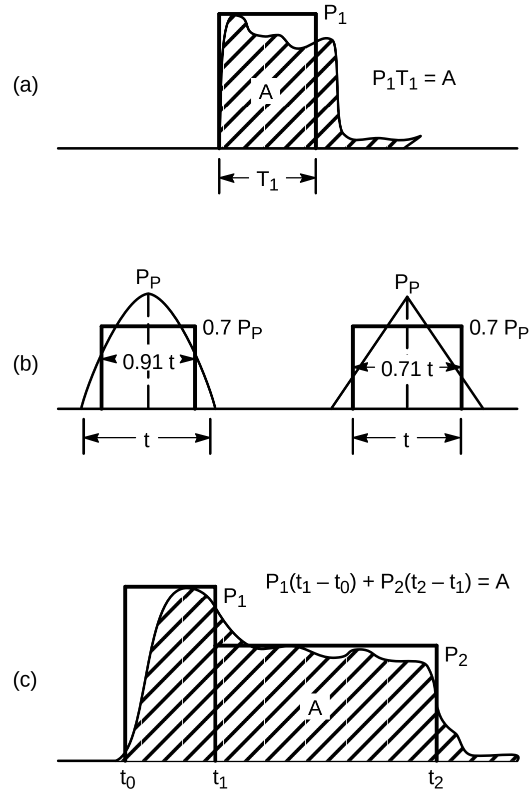

Figure 7. Modeling of Power Pulses

- A power pulse having a $\sin^2$ shape models as a triangular waveform.

Power pulses having more complex waveforms could be modeled by using two or more pulses as shown in Figure 7c.

A point to remember is that a high amplitude pulse of a given amount of energy will produce a higher rise in junction temperature than will a lower amplitude pulse of longer duration having the same energy.

As an example, the case of a transistor used in a dc to ac power converter will be analyzed. The idealized waveforms of collector current, I_C, collector to emitter voltage, V_{CE}, and power dissipation P_D, are shown in Figure 8.

A model of the power dissipation is shown in Figure 8d. This switching transient of the model is made, as was suggested, for a triangular pulse.

For example, T_J at the end of the rise, on, and fall times, T_1, T_2 and T_3 respectively, will be found.

Conditions:

TO–3 package,

$R_{\theta JC}$ = 0.5°C/W, I_C = 60 A, $V_{CE(off)}$ = 60 V
T_A = 50°C
t_f = 80 µs, t_r = 20 µs
$V_{CE(sat)}$ = 0.3 V @ 60 A
Frequency = 2 kHz ∴ τ = 500 µs
P_{on} = (60)(0.3) = 18 W
$P_f = 30 \times 30 = 900$ W = P_r

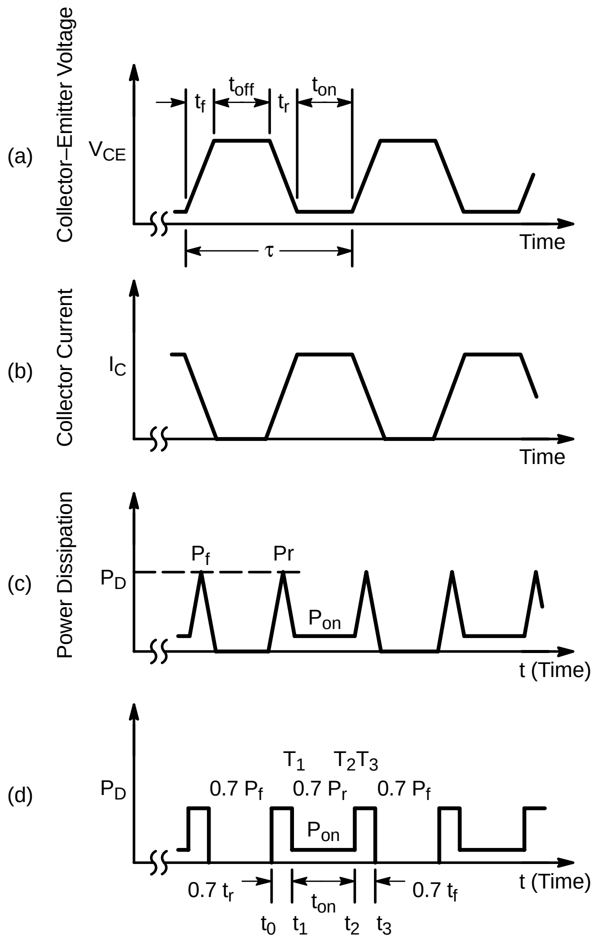

Figure 8. Idealized Waveforms of I_C, V_{CE} and P_D in a DC to AC Inverter

Assume that the response curve in Figure C3 for a die area of 58,000 square mils applies. Also, that the device is mounted on an MS–15 heat sink using Dow Corning DC340 silicone compound with an air flow of 1.0 lb/min flowing across the heat–sink. (From MS–15 Data Sheet, $R_{\theta CS}$ = 0.1°C/W and $R_{\theta SA}$ = 0.55°C/W.)

Procedure: Average each pulse over the period using equation 1–3 (Appendix A, Method 2), i.e.,

$$P_{avg} = 0.7P_r\,0.71\frac{t_r}{\tau} + P_{on}\frac{t_{on}}{\tau} + 0.7P_f\,0.71\frac{t_f}{\tau}$$

$$= (0.7)(900)(0.71)\frac{(20)}{500} + (18)\frac{(150)}{500}$$

$$+ (0.7)(900)(0.71)\frac{80}{500}$$

$$= 17.9 + 5.4 + 71.5$$

$$= 94.8 \text{ W}$$

From equation 1–4, Method 2A:

$$T_1[P_{avg} + (0.7P_r - P_{avg}) \cdot r(t_1 - t_o)]R_{\theta JC}$$

At this point it is observed that the thermal response curves of Figure C3 do not extend below 100 µs. Heat transfer theory for one dimensional heat flow indicates that the response curve should follow the $\sqrt{t}$ law at small times. Using this as a basis for extending the curve, the response at 14.2 µs is found to be 0.023.

We then have:

$$T_1 = [94.8 + (630 - 94.8)0.023](0.5)$$

$$= (107.11)(0.5) = 53.55^\circ C$$

For T_2 we have, by using superposition:

$$T_2 = [P_{avg} - P_{avg} \cdot r(t_2 - t_o) + 0.7P_r \cdot r(t_2 - t_o)$$

$$- 0.7P_r \cdot r(t_2 - t_1) + P_{on} \cdot r(t_2 - t_1)]R_{\theta JC}$$

$$= [P_{avg} + (0.7P_r - P_{avg}) \cdot r(t_2 - t_o)$$

$$+ (P_{on} - 0.7P_r) \cdot r(t_2 - t_1)]R_{\theta JC}$$

$$= [94.8 + (630 - 94.8) \cdot r(164\ \mu s)$$

$$+ (18 - 630) \cdot r(150\ \mu s)](0.5)$$

$$= [94.8 + (535.2)(0.079) - (612)(0.075)](0.5)$$

$$= [94.8 + 42.3 - 45.9](0.5)$$

$$= (91.2)(0.5) = 45.6^\circ C$$

For the final point T_3 we have:

$$T_3 = [P_{avg} - P_{avg} \cdot r(t_3 - t_o) + 0.7P_r \cdot r(t_3 - t_o)$$

$$- 0.7P_r \cdot r(t_3 - t_1) + P_{on} \cdot r(t_3 - t_1)$$

$$- P_{on} \cdot r(t_3 - t_2) + 0.7P_f \cdot r(t_3 - t_2)]R_{\theta JC}$$

$$= [P_{avg} + (0.7P_r - P_{avg}) \cdot r(t_3 - t_o)$$

$$+ (P_{on} - 0.7P_r) \cdot r(t_3 - t_1) + (0.7P_r - P_{on})$$

$$\cdot r(t_3 - t_2)]R_{\theta JC}$$

$$= [94.8 + (535.2) \cdot r(221\ \mu s) + (-612)$$

$$\cdot r(206.8\ \mu s) + (612) \cdot r(56.8\ \mu s)](0.5)$$

$$= [94.8 + (535.2)(0.09) - (612)(0.086)$$

$$+ (612)(0.045)](0.5)$$

$$= [94.8 + 481.7 - 52.63 + 27.54](0.5)$$

$$= (117.88)(0.5) = 58.94^\circ C$$

The junction temperature at the end of the rise, on, and fall times, T_{J1}, T_{J2}, and T_{J3}, is as follows:

$$T_{J1} = T_1 + T_A + R_{\theta CA} \cdot P_{avg}$$

$$R_{\theta CA} = R_{\theta CS} + R_{\theta SA} = 0.1 + 0.55$$

$$T_{J1} = 53.55 + 50 + (0.65)(94.8) = 165.17^\circ C$$

$$T_{J2} = T_2 + T_A + R_{\theta CA} \cdot P_{avg}$$
$$= 45.6 + 50 + (0.65)(94.8)$$
$$= 157.22^\circ C$$
$$T_{J3} = T_3 + T_A + R_{\theta CA} \cdot P_{avg}$$
$$= 58.94 + 50 + (0.65)(94.8)$$
$$= 170.56^\circ C$$
$$T_{J(avg)} = P_{avg}(R_{\theta JC} + R_{\theta CS} + R_{\theta SA}) + T_A$$
$$= (94.8)(0.5 + 0.1 + 0.55) + 50$$
$$= (94.8)(1.15) + 50 = 159.02^\circ C$$

Inspection of the results of the calculations T_1, T_2, and T_3 reveal that the term of significance in the equations is the average power. Even with the poor switching times there was a peak junction temperature of 11.5°C above the average value. This is a 7% increase which for most applications could be ignored, especially when switching times are considerably less. Thus the product of average power and steady–state thermal resistance is the determining factor for junction temperature rise in this application.

Summary

This report has explained the concept of transient thermal resistance and its use. Methods using various degrees of approximations have been presented to determine the junction temperature rise of a device. Since the thermal response data shown is a step function response, modeling of different wave shapes to an equivalent rectangular pulse of pulses has been discussed.

The concept of a duty cycle family of curves has also been covered; a concept that can be used to simplify calculation of the junction temperature rise under a repetitive pulse train.

Safe area and surge ratings must also be observed. It is possible to have T_J well below $T_{J(max)}$ as calculated from the thermal response curves, yet have a hot–spot in the semiconductor which will cause a failure.

APPENDIX A METHODS OF SOLUTION

In the examples, a type 2N3647 transistor will be used; its steady–state thermal resistance, $R_{\theta JC}$, is 35°C/W and its value for r(t) is shown in Figure A1.

Definitions:

$P_1, P_2, P_3 \ldots P_n$ = power pulses (Watts)

$T_1, T_2, T_3 \ldots T_n$ = junction to case temperature at end of $P_1, P_2, P_3 \ldots P_n$

$t_0, t_1, t_2, \ldots t_n$ = times at which a power pulse begins or ends

$r(t_n - t_k)$ = transient thermal resistance factor at end of time interval $(t_n - t_k)$

Table 1. Several Possible Methods of Solutions

1. Junction Temperature Rise Using Pulse–by–Pulse Method
   A. Temperature rise at the end of the n_{th} pulse for pulses with unequal amplitude, spacing, and duration.
   B. Temperature rise at the end of the n_{th} pulse for pulses with equal amplitude, spacing, and duration.
2. Temperature Rise Using Average Power Concept Under Steady–State Conditions for Pulses of Equal Amplitude, Spacing, and Duration
   A. At the end of the n_{th} pulse.
   B. At the end of the (n + 1) pulse.
3. Temperature Rise Using Average Power Concept Under Transient Conditions.
   A. At the end of the n_{th} pulse for pulses of equal amplitude, spacing and duration.
   B. At the end of the n + 1 pulse for pulses of equal amplitude, spacing and duration.
   C. At the end of the n_{th} pulse for pulses of unequal amplitude, spacing and duration.
   D. At the end of the n + 1 pulse for pulses of unequal amplitude, spacing and duration.

Method 1A – Finding T_J at the End of the Nth Pulse in a Train of Unequal Amplitude, Spacing, and Duration

General Equation:

$$T_n = \sum_{i=1}^{n} P_i[r(t_{2n-1} - t_{2i-2}) - r(t_{2n-1} - t_{2i-1})]R_{\theta JC} \qquad (1–1)$$

where n is the number of pulses and P_i is the peak value of the i^{th} pulse.

To find temperature at the end of the first three pulses, Equation 1–1 becomes:

$$T_1 = P_1 r(t_1) R_{\theta JC} \qquad (1–1A)$$

$$T_2 = [P_1 r(t_3) - P_1 r(t_3 - t_1) + P_2 r(t_3 - t_2)]R_{\theta JC} \qquad (1–1B)$$

$$T_3 = [P_1 r(t_5) - p_1 r(t_5 - t_1) + P_2 r(t_5 - t_2) - P_2 r(t_5 - t_3) + P_3 r(t_5 - t_4)]R_{\theta JC} \qquad (1–1C)$$

Example:

Conditions are shown in Figure 4 as:

$P_1 = 40$ W	$t_0 = 0$	$t_3 = 1.3$ ms
$P_2 = 20$ W	$t_1 = 0.1$ ms	$t_4 = 3.3$ ms
$P_3 = 30$ W	$t_2 = 0.3$ ms	$t_5 = 3.5$ ms

Therefore,

$t_1 - t_0 = 0.1$ ms	$t_3 - t_1 = 1.2$ ms
$t_2 - t_1 = 0.2$ ms	$t_5 - t_1 = 3.4$ ms
$t_3 - t_2 = 1$ ms	$t_5 - t_2 = 3.2$ ms
$t_4 - t_3 = 2$ ms	$t_5 - t_3 = 2.2$ ms
$t_5 - t_4 = 0.2$ ms	

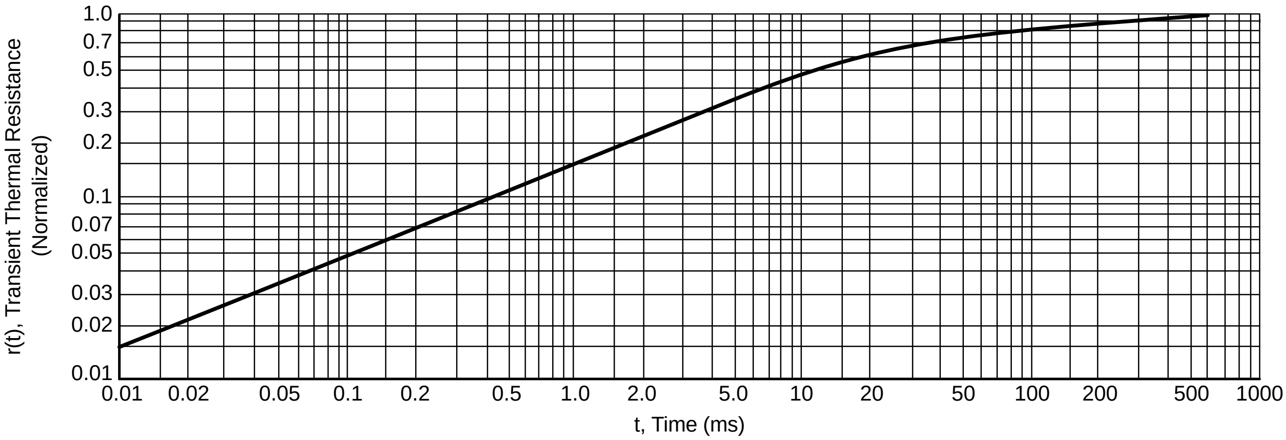

Figure 1. 2N3467 Transient Thermal Response

Procedure:

Find $r(t_n - t_k)$ for preceding time intervals from Figure 2, then substitute into Equations 1–1A, B, and C.

$$T_1 = P_1 r(t_1) R_{\theta JC} = 40 \cdot 0.05 \cdot 35 = 70^\circ C$$

$$T_2 = [P_1 r(t_3) - P_1 r(t_3 - t_1) + P_2 r(t_3 - t_2)] R_{\theta JC}$$

$$= [40(0.175) - 40(0.170) + 20(0.155)]35$$

$$= [40(0.175 - 0.170) + 20(0.155)]35$$

$$= [0.2 + 3.1]35 = 115.5^\circ C$$

$$T_3 = [P_1 r(t_5) - p_1 r(t_5 - t_1) + P_2 r(t_5 - t_2)$$

$$- P_2 r(t_5 - t_3) + P_3 r(t_5 - t_4)] R_{\theta JC}$$

$$= [40(0.28) - 40(0.277) + 20(0.275) - 20(0.227)$$

$$+ 30(0.07)]35$$

$$= [40(0.28 - 0.277) + 20(0.275 - 0.227)$$

$$+ 30(0.07)]35$$

$$= [0.12 + 0.96 + 2.1]^\dagger\, 35 = 3.18 \cdot 35 = 111.3^\circ C$$

†Relative amounts of temperature residual from P_1, P_2, and P_3 respectively are indicated by the terms in brackets.

Note, by inspecting the last bracketed term in the equations above that very little residual temperature is left from the first pulse at the end of the second and third pulse. Also note that the second pulse gave the highest value of junction temperature, a fact not so obvious from inspection of the figure. However, considerable residual temperature from the second pulse was present at the end of the third pulse.

Method 1B – Finding T_J at the End of the Nth Pulse in a Train of Equal Amplitude, Spacing, and Duration

The general equation for a train of equal repetitive pulses can be derived from Equation 1–1. $P_i = P_D$, $t_i = t$, and the spacing between leading edges or trailing edges of adjacent pulses is τ.

General Equation:

$$T_n = P_D R_{\theta JC} \sum_{i=1}^{n} r[(n - i)\tau + t] - r[(n - i)\tau] \qquad (1\text{–}2)$$

Expanding:

$$T_n = P_D R_{\theta JC} r[(n - 1)\tau + t] - r[(n - 1)\tau] \qquad (1\text{–}2A)$$

$$+ r[(n - 2)\tau + t] - r[(n - 2)\tau] + r[(n - 3)\tau + t]$$

$$- r[(n - 3)\tau] + ... + r[(n - i)\tau + t]$$

$$- r[(n - i)\tau] ... + r[(t)]$$

For 5 pulses, equation 1–2A is written:

$$T_5 = P_D R_{\theta JC}[r(4\tau + t) - r(4\tau) + r(3\tau + t) - r(3\tau)$$

$$+ r(2\tau + t) - r(2\tau) + r(\tau + t) - r(\tau) + r(t)]$$

Example:

Conditions are shown in Figure 5 substituting values into the preceding expression:

$$T_5 = (5)(35)[r(4.20 + 5) - r(4.20) + r(3.20 + 5)$$

$$+ r(3.20) + r(2.20 + 5) - r(2.20) + r(20 + 5)$$

$$- r(20) + r(5)]$$

$$T_5 = (5)(35)[0.6 - 0.76 + 0.73 - 0.72 + 0.68$$

$$- 0.66 + 0.59 - 0.55 + 0.33] = (5)(35)(0.40)$$

$$T_5 = 70.0^\circ C$$

Note that the solution involves the difference between terms nearly identical in value. Greater accuracy will be obtained with long or repetitive pulse trains using the technique of an average power pulse as used in Methods 2 and 3.

Method 2 – Average Power Method, Steady–State Condition

The essence of this method is shown in Figure 6. Pulses previous to the n_{th} pulse are averaged. Temperature due to the n_{th} or n + 1 pulse is then calculated and combined properly with the average temperature.

Assuming the pulse train has been applied for a period of time (long enough for steady–state conditions to be established), we can average the power applied as:

$$P_{avg} = P_D \frac{t}{\tau} \quad (1–3)$$

Method 2A – Finding Temperature at the End of the N_{th} Pulse

Applicable Equation:

$$T_n = [P_{avg} + (P_D - P_{avg})r(t)]R_{\theta JC} \quad (1–4)$$

or, by substituting Equation 1–3 into 1–4,

$$T_n = \left[\frac{t}{\tau} + \left(1 - \frac{t}{\tau}\right)r(t)\right]P_D R_{\theta JC} \quad (1–5)$$

The result of this equation will be conservative as it adds a temperature increase due to the pulse (P_D – P_{avg}) to the average temperature. The cooling between pulses has not been accurately accounted for; i.e., T_J must actually be less than $T_{J(avg)}$ when the n_{th} pulse is applied.

Example: Find T_n for conditions of Figure 5.

Procedure: Find P_{avg} from equation (1–3) and substitute values in equation (1–4) or (1–5).

$$T_n = [(1.25) + (5.0 - 1.25)(0.33)](35)$$
$$= 43.7 + 43.2 = 86.9^\circ C$$

Method 2B – Finding Temperature at the End of the N + 1 Pulse

Applicable Equation:

$$T_{n+1} = [P_{avg} + (P_D - P_{avg})r(t + \tau) + P_D r(t) - P_D r(\tau)]R_{\theta JC} \quad (1–6)$$

or, by substituting equation 1–3 into 1–6,

$$T_{n+1} = \left[\frac{t}{\tau} + \left(1 - \frac{t}{\tau}\right)r(t + \tau) + r(t) - r(\tau)\right]P_D R_{\theta JC} \quad (1–7)$$

Example: Find T_n for conditions of Figure 5.

Procedure: Find P_{avg} from equation (1–3) and substitute into equation (1–6) or (1–7).

$$T_{n+1} = [(1.25) + (5 - 1.25)(0.59) + (5)(0.33) - (5)(0.56)](35) = 80.9^\circ C$$

Equation (1–6) gives a lower and more accurate value for temperature than equation (1–4). However, it too gives a higher value than the true T_J at the end of the n + 1 pulse. The error occurs because the implied value for T_J at the end of the n_{th} pulse, as was pointed out, is somewhat high. Adding additional pulses will improve the accuracy of the calculation up to the point where terms of nearly equal value are being subtracted, as shown in the examples using the pulse–by–pulse method. In practice, however, use of this method has been found to yield reasonable design values and is the method used to determine the duty cycle of family of curves – e.g., Figure 2.

Note that the calculated temperature of 80.9°C is 10.9°C higher than the result of example 1B, where the temperature was found at the end of the 5th pulse. Since the thermal response curve indicated thermal equilibrium in 1 second, 50 pulses occurring 20 milliseconds apart will be required to achieve stable average and peak temperatures; therefore, steady state–conditions were not achieved at the end of the 5th pulse.

Method 3 – Average Power Method, Transient Conditions

The idea of using average power can also be used in the transient condition for a train of repetitive pulses. The previously developed equations are used but P_{avg} must be modified by the thermal response factor at time $t_{(2n–1)}$.

Method 3A – Finding Temperature at the End of the Nth Pulse for Pulses of Equal Amplitude, Spacing and Duration

Application Equation:

$$T_n = \left[\frac{t}{\tau} r\, t_{(2n-1)} + \left(1 - \frac{t}{\tau}\right)r(t)\right]P_D R_{\theta JC} \quad (1–8)$$

Conditions: (see Figure 5)

Procedure: At the end of the 5th pulse (see Figure 7).

$$T_5 = [5/20 \cdot r(85) + (1 - 5/20)r(5)](5)(35)$$
$$= [(0.25)(0.765) + (0.75)(0.33)](175)$$
$$= 77^\circ C$$

This value is a little higher than the one calculated by summing the results of all pulses; indeed it should be, because not cooling time was allowed between P_{avg} and the n_{th} pulse. The method whereby temperature was calculated at the n + 1 pulse could be used for greater accuracy.

Method 3B – Finding Temperature at the End of the N + 1 Pulse for Pulses of Equal Amplitude, Spacing and Duration

Application Equation:

$$T_{n+1} = \left[\frac{t}{\tau} r(t_{2n-1}) + \left(1 - \frac{t}{\tau}\right)r(t + \tau) + r(t) - r(\tau)\right]P_D R_{\theta JC} \quad (1–9)$$

Example: Conditions as shown in Figure 5. Find temperature at the end of the 5th pulse.

For n + 1 = 5, n = 4, $t_{2n–1}$ = t_7 = 65 ms,

$$T_5 = \left[\frac{5}{20} r(65\text{ ms}) + \left(1 - \frac{5}{20}\right)r(25\text{ ms}) + r(5\text{ms}) - r(20\text{ ms})\right](5)(35)$$

$$T_5 = [(0.25)(0.73) + (0.75)(0.59) + 0.33 - 0.55](5)(35)$$

$$T_5 = 70.8^\circ C$$

The answer agrees quite well with the answer of Method 1B where the pulse–by–pulse method was used for a repetitive train.

Method 3C – Finding T_J at the End of the Nth Pulse in a Random Train

The technique of using average power does not limit itself to a train of repetitive pulses. It can be used also where the pulses are of unequal magnitude and duration. Since the method yields a conservative value of junction temperature rise it is a relatively simple way to achieve a first approximation. For random pulses, equations 1–4 through 1–7 can be modified. It is necessary to multiply P_{avg} by the thermal response factor at time $t_{(2n-1)}$. P_{avg} is determined by averaging the power pulses from time of application to the time when the last pulse starts.

Application Equations:

General:

$$P_{avg} = \sum_{i=1}^{n} P_i \frac{t_{(2i-1)} - t_{(2i-2)}}{t_{(2n)} - t_{(2i-2)}} \qquad (1–10)$$

For 3 Pulses:

$$P_{avg} = P_1 \frac{t_1 - t_0}{t_4 - t_0} + P_2 \frac{t_3 - t_2}{t_4 - t_2} \qquad (1–11)$$

Example: Conditions are shown in Figure 4 (refer to Method 1A).

Procedure: Find P_{avg} from equation 1–3 and the junction temperature rise from equation 1–4.

Conditions: Figure 4

$$P_{avg} = 40 \cdot \frac{0.1}{3.3} + 20\frac{1}{3} = 1.21 + 6.67$$

$$= 7.88 \text{ Watts}$$

$$T_3 = [P_{avg} r(t_5) + (P_3 - P_{avg}) r(t_5 - t_4)] R_{\theta JC}$$

$$= [7.88(0.28) + (30 - 7.88) \cdot 0.07]35$$

$$= [2.21 + 1.56]35 = 132^\circ C$$

This result is high because in the actual case considerable cooling time occurred between P_2 and P_3 which allowed T_J to become very close to T_C. Better accuracy is obtained when several pulses are present by using equation 1–10 in order to calculate $T_J - t_C$ at the end of the n_{th} + 1 pulse. This technique provides a conservative quick answer if it is easy to determine which pulse in the train will cause maximum junction temperature.

Method 3D – Finding Temperature at the End of the N + 1 Pulse in a Random Train

The method is similar to 3C and the procedure is identical. P_{avg} is calculated from Equation 1–10 modified by $r(t_{2n-1})$ and substituted into equation 1–6, i.e.,

$$T_{n+1} = [P_{avg} r(t_{2n-1}) + (P_D - P_{avg}) r(t_{2n-1} - t_{2n-2})$$
$$+ P_D r(t_{2n+1} - t_{2n}) - P_D r(t_{2n+1} - t_{2n-1})] R_{\theta JC}$$

The previous example can not be worked out for the n + 1 pulse because only 3 pulses are present.

Table 2. Summary of Numerical Solution for the Repetitive Pulse Train of Figure 5

Temperature Desired	Temperature Obtained, °C		
	Pulse–by–Pulse	Average Power Nth Pulse	Average Power N + 1 Pulse
At End of 5th Pulse	70.0 (1B)	77 (3A)	70.8 (3B)
Steady State Peak	–	86.9 (2A)	80.9 (2B)

NOTE: Number in parenthesis is method used.

APPENDIX B THERMAL RESPONSE MEASUREMENTS

To measure the thermal response of a semiconductor, a temperature sensitive parameter of the device is used as an indicator of device temperature. Other methods are impractical on a completely assembled device. If the parameter varies linearly with temperature, finding thermal response is greatly simplified since the measured parameter value will be directly proportional to temperature.

The forward voltage drop of a diode or SCR or the collector–base junction of a transistor, when operated a low currents, has a linear voltage change with temperature and is a good choice for the temperature sensitive parameter. Since the collector–base junction of a transistor is reversed biased when power is dissipated, a measurement using the forward V_{CB} must be made during the cooling interval. A suitable measurement procedure is to dissipate power long enough to achieve thermal equilibrium while periodically switching the circuit to shut–off the power, forward–bias the collector–base junction, and monitor its change in voltage as the device cools off. The switching must be performed rapidly or the initial part of the response will not be seen.

A circuit that can be used to measure thermal resistance or thermal response of a power transistor is shown in Figure B1. With the transistor under test (T.U.T.) in the circuit, the power–sense switch (SW_2) is set in the sense position which removes the emitter current supply and the base return from the transistor. After the collector supply is set at a suitable value, the sense supply is adjusted to allow a low–level sense current through the base–collector junction. Note that the sense current flows in the opposite direction from that of the collector current; thus, a reversing switch on the collector current meter is needed to set the sense current level.

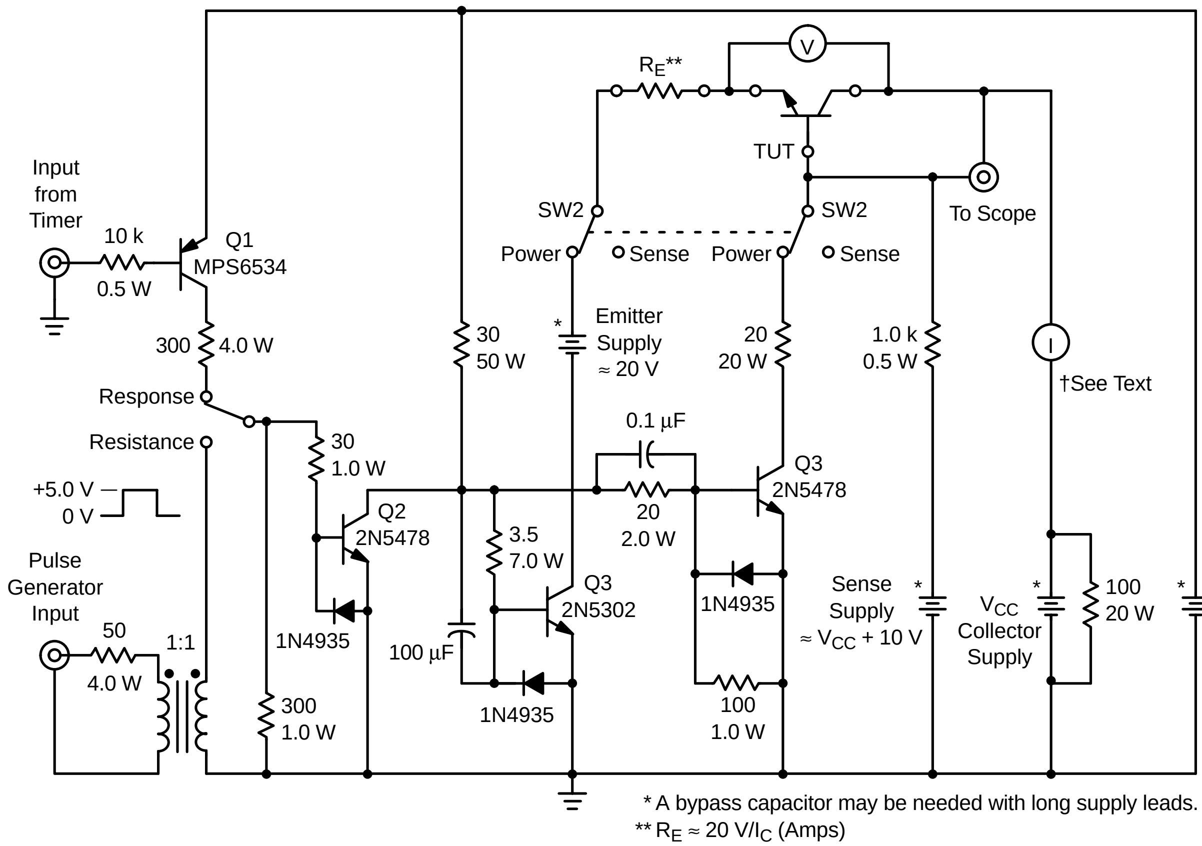

Figure B1. Thermal Resistance/Response Test Fixture for NPN Power Transistors Up to 10 Amperes Collector Current

Switch SW_2 is then set at the power position and the emitter supply is connected. With SW_1 in the response position, a positive voltage pulse, slightly greater than the auxiliary supply, from a timer circuit is needed to cycle the T.U.T. The timer must provide a pulse of sufficient length to allow the T.U.T. to achieve thermal equilibrium. At this time, transistors Q1 and Q2 are off and Q3 and Q4 are on. When the output of the timer changes to a low state, Q1 and Q2 turn on and Q3 and Q4 turn off. Thus, the only current flowing through the transistor is the collector–base sense current which allows the collector–base voltage to be monitored by an oscilloscope. The response curve is photographed at different sweep rates to facilitate plotting.

The period of the timer output pulse must be variable in order to allow thermal equilibrium to be achieved for different types of transistors. Also, the cooling time must be at least equal to the heating time to allow the junction temperature to cool to its original value.

Case mounted semiconductors should be mounted on a heat sink that will hold the case at a nearly constant temperature. In other words, the thermal resistance from the transistor case to the heat sink should be negligible compared to the junction–to–case thermal resistance. If this precaution is not taken, the results will be influenced by the response (the change in temperature) of the heat sink.

With SW_1 in the thermal resistance position, steady–state thermal resistance can be measured. For this measurement, the T.U.T. is on most of the time; a narrow pulse is used to turn the T.U.T. off to allow sensing of the junction temperature. The forward voltage drop vs. temperature must be known in order to calculate thermal resistance.

Figure B2 is a thermal resistance/response test fixture for SCRs and rectifiers. Operation of this text fixture is similar to the NPN test fixture except that switch SW_3 is added to provide gate drive to turn the SCR on. When testing SCRs, the current sense level must be above the holding current.

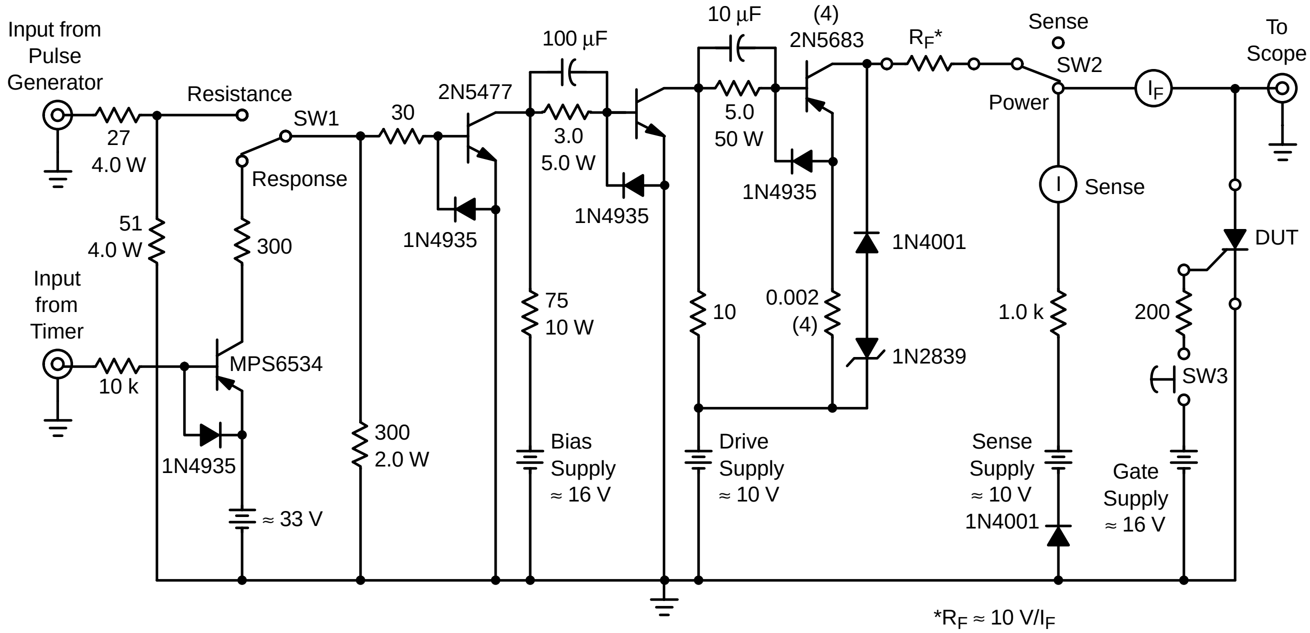

Figure B2. Thermal Resistance/Response Test Fixture for SCR's and Rectifiers Up to 50 Amperes Forward Current

APPENDIX C TRANSIENT THERMAL RESPONSE CURVES

The data presented in this appendix is for the purpose of enabling a reasonable estimate of transient thermal resistance to be made in situations where data is not readily available. As can be seen by studying Figure 1, the normalized response values cover a range of about 10:1 in the time region between 100 µs and 10 ms for the whole gamut of power transistor packages and die areas offered by ON Semiconductor. In this section, data is supplied for a number of packages, each having several different die sizes, so that a closer estimate of response can be made.

Each figure indicates some representative part numbers for the given curves; obviously, space limitations prevent listing all parts for which the curves apply. As an additional aid, Figure C11 may be used to estimate die area from thermal resistance information. Figure C11 is not applicable to Darlington transistors and other dual devices or integrated circuits, as the ratio of active transistors and other dual devices or integrated circuits, as the ratio of active transistor area to total die area is different from that of the transistors used to prepare the figure.

Measurement of thermal response can hardly be regarded as an exact science. As a result of switching, transients occur which make it very difficult to ascertain response below 100 µs. One dimensional heat flow theory predicts that temperature will be proportional to the square root of time; even though this relationship is not always observed, it is generally used to extrapolate data below 100 µs.

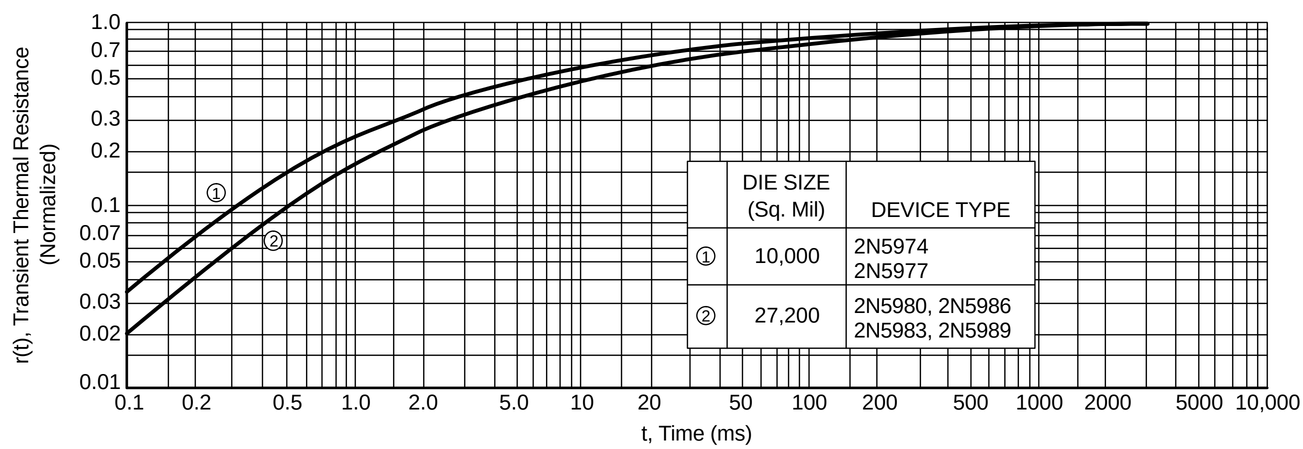

Figure C1. Case 90 and 199 (Thermopad) Thermal Response

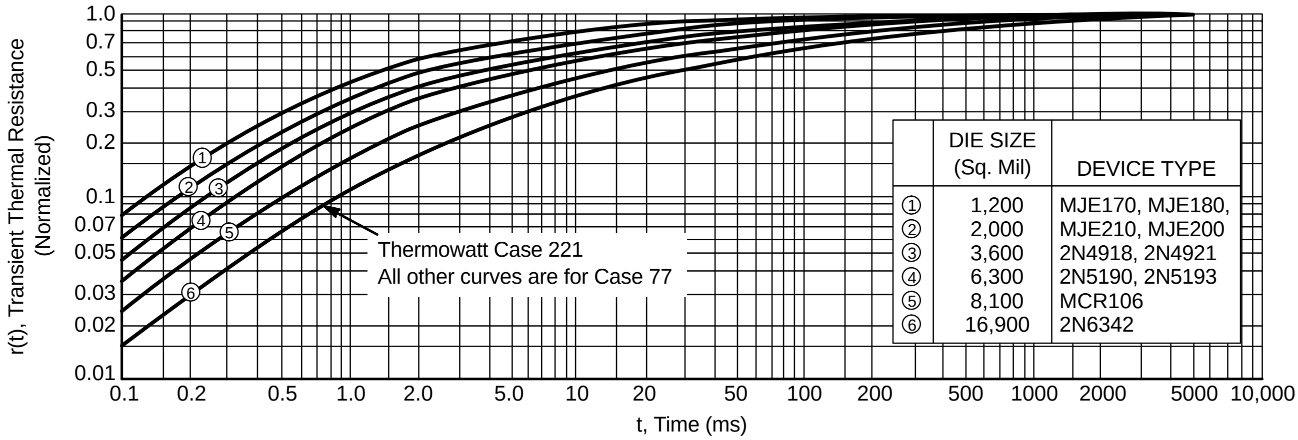

Figure C2. Case 90 and 199 (Thermopad) Thermal Response

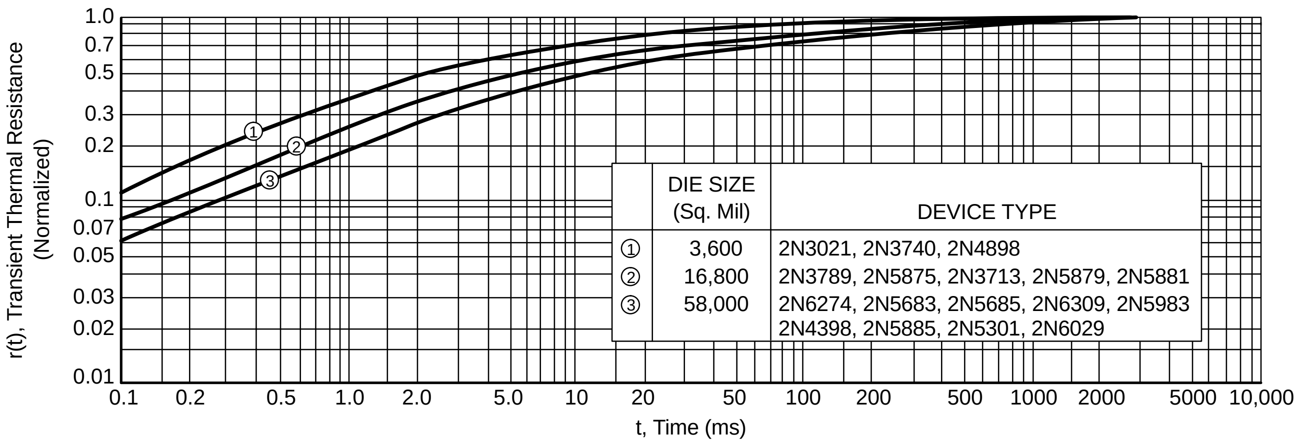

Figure C3. TO–3 and TO–66 (Diamond) Thermal Response. Data Applies to Packages Which Are All Copper or Contain a Copper Slug Under the Die

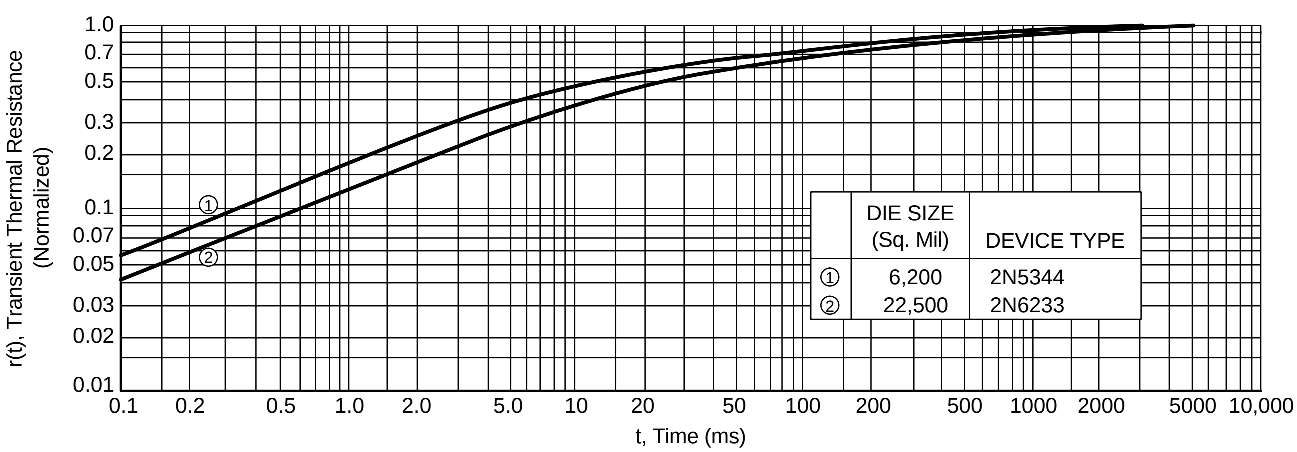

Figure C4. TO–66 Thermal Response, All Steel Package

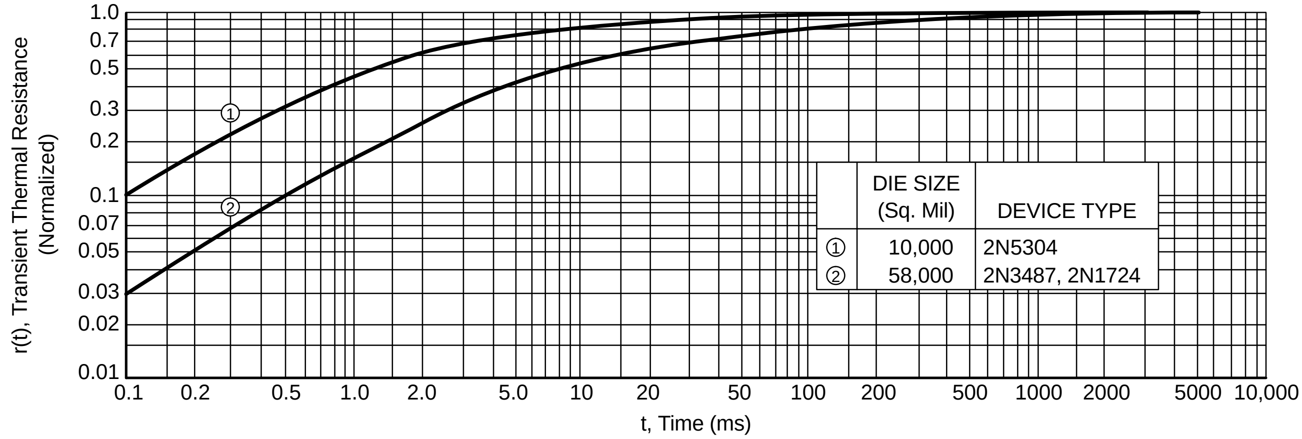

Figure C5. TO–61 (11/16″ Hex, Stud Mount) Thermal Response

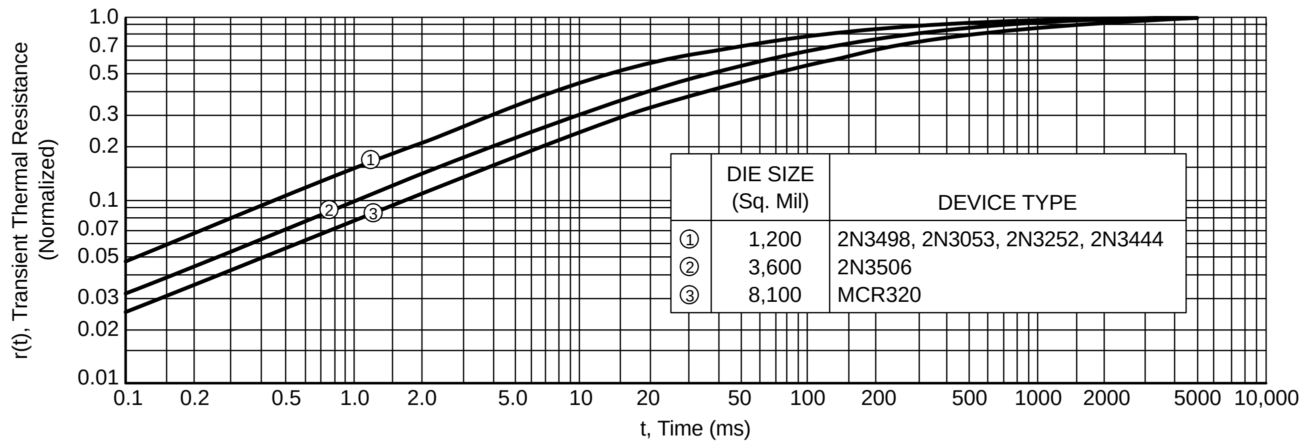

Figure C6. TO–5 (Solid Kovar Header) Thermal Response

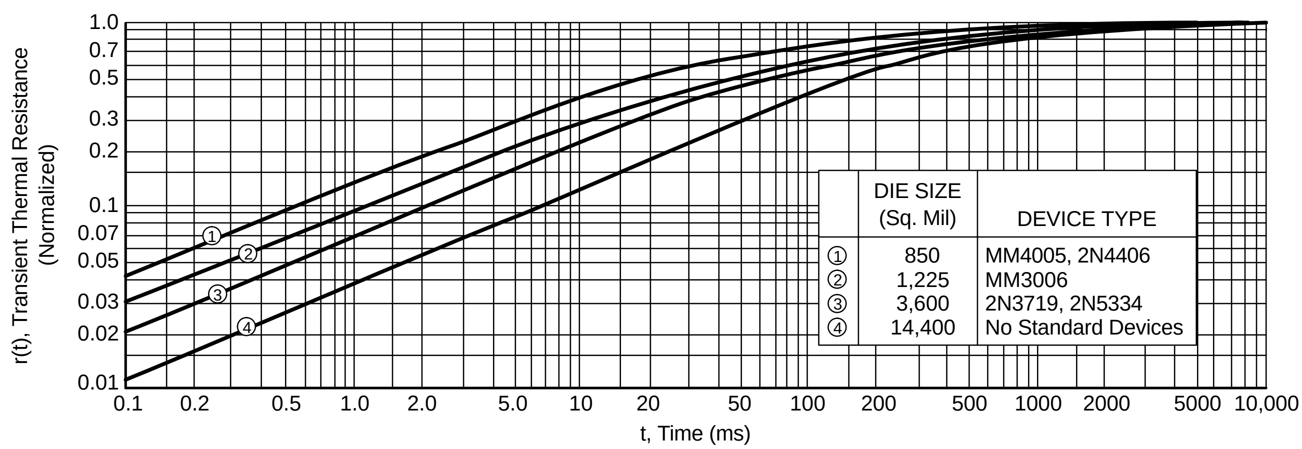

Figure C7. TO–5 (Solid Steel Header) Thermal Response

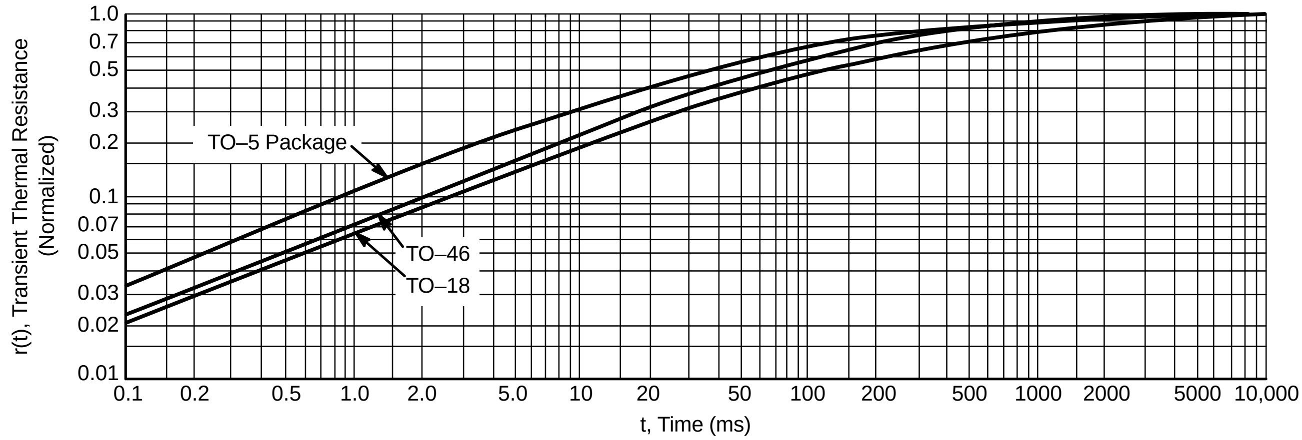

Figure C8. Shell Header TO–5, TO–18 and TO–46 Thermal Response, Applies to All Commonly Used Die

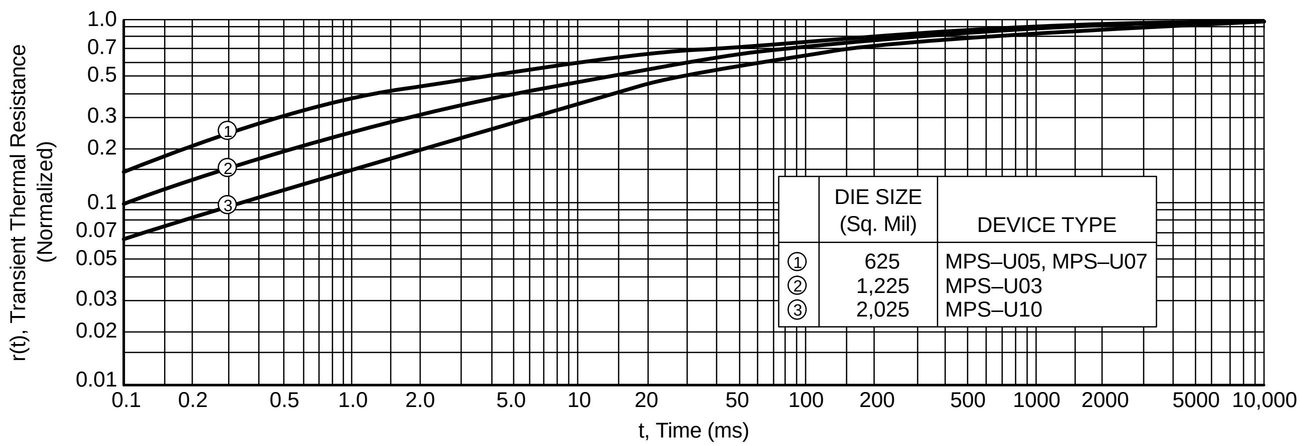

Figure C9. Case 152 (Uniwatt) Thermal Response

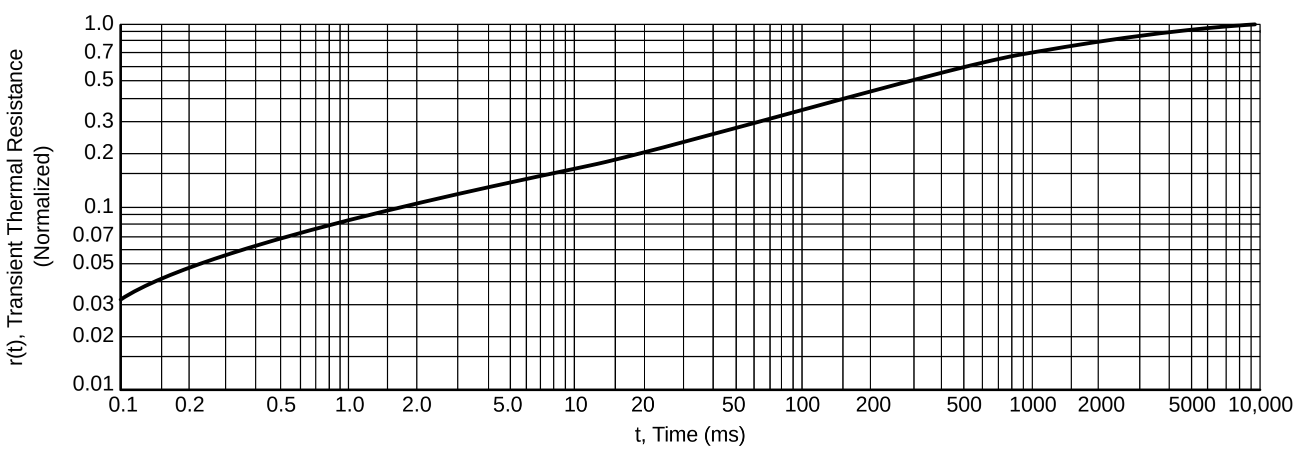

Figure C10. TO–92 (Unibloc) Thermal Response, Applies to All Commonly Used Die

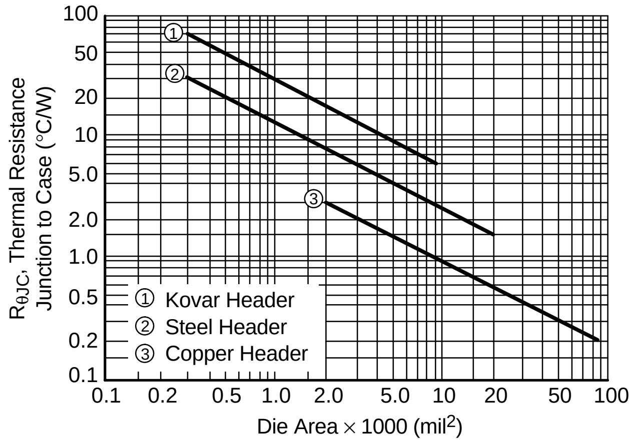

Figure C11. Typical Thermal Resistance As a Function of Case Material and Die Area. Data Applies to Solid Header Parts Only. Use Copper Curve for Aluminum and Steel Packages With a Copper Slug Under the Die, Which Is the Standard ON Semiconductor Design.

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2. Lockett, R. A., Bell, H. A., Priston, R. “Thermal Resistance of Low Power Semiconductor Devices Under Pulse Conditions,” Mullard Technical Communications, No. 76, July, 1965.

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