AN-292
Application Note

THERMAL RESPONSE OF SEMICONDUCTORS

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To design reliable semiconductor circuits, it is necessary to hold junction temperature below its maximum rating, regardless of operating conditions. Heretofore, little information has been available to determine junction temperature under pulsed power conditions such as are encountered in switching circuits. This note explains a workable method – using the concept of transient thermal resistance – which enables the designer to predict junction temperature at any point in time regardless of the power waveform.

MOTOROLA Semiconductor Products Inc.

THERMAL RESPONSE OF SEMICONDUCTORS

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:

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

where T_J = junction temperature
T_R = temperature at reference point
P_D = power dissipated in the junction
θ_{JR} = steady-state thermal resistance from junction to a temperature reference.

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

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

$T_{J(max)}$ 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 θ_{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, secondary breakdown* may occur at power levels less than that given by equation (1b). Secondary 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 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 capacity of the system has not been taken into account.

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:

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

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; (i.e., $T_J \propto \sqrt{t}$) a fact found true of all devices measured. The curves shown are for a variety of transistor types ranging from rather small devices in TO-5 glass header package (curve 6) to a large 10 ampere transistor in a TO-3 package (curve 2). Observe that the total percentage difference is less than 4:1 in the short pulse ($\sqrt{t}$) region. The values of thermal resistance vary over 50:1, however. Therefore, the curves could be applied with judgement to any semiconductor type. The package is the most important single variable which affects thermal response.

Recent Motorola 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 = O 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 quite 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 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.

*Secondary breakdown is a result of current concentrating to 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. See AN-415.

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 2N3467 transistor.

Pulse power P_D = 5 Watts
Duration t = 5 milliseconds
Period τ_p = 20 milliseconds
Case temperature, T_C = 75°C
Junction to case thermal resistance,
θ_{JC} = 35°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:

$$T_J = r(5\ ms)\,\theta_{JC} P_D + T_C$$

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

$$\therefore T_J = 0.33 \times 35 \times 5 + 75 = 57.8^\circ C + 75 = 132.8^\circ C$$

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

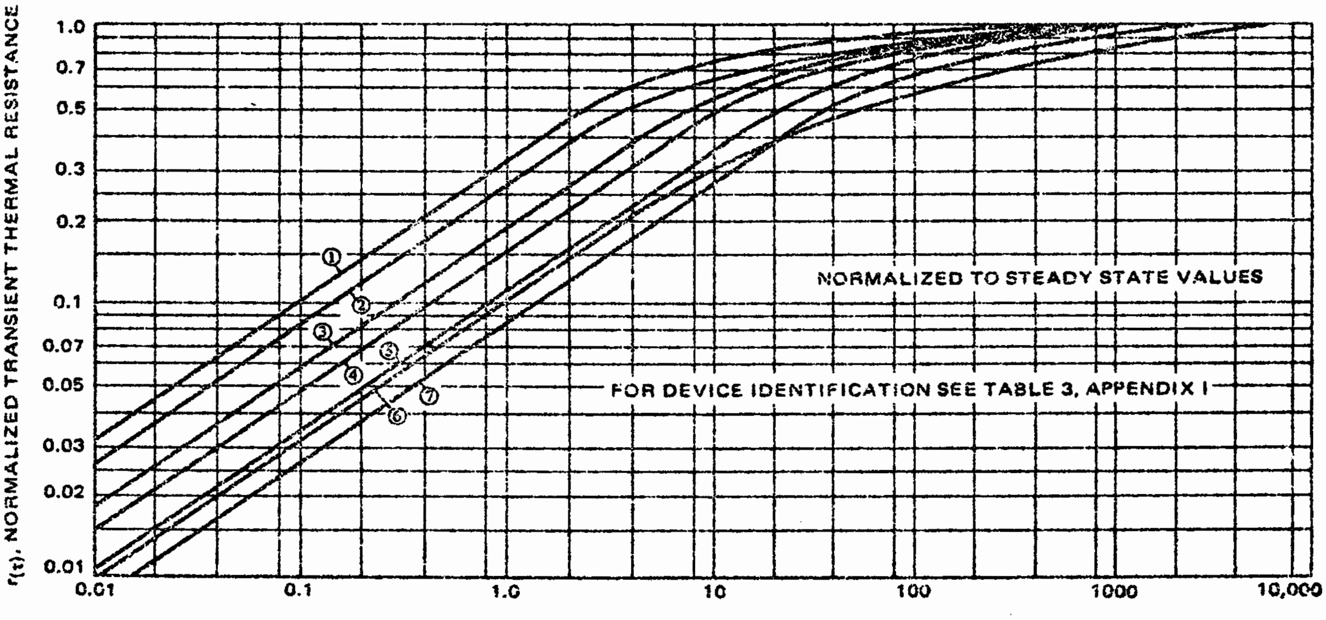

FIGURE 1 – Thermal response of various transistor types.

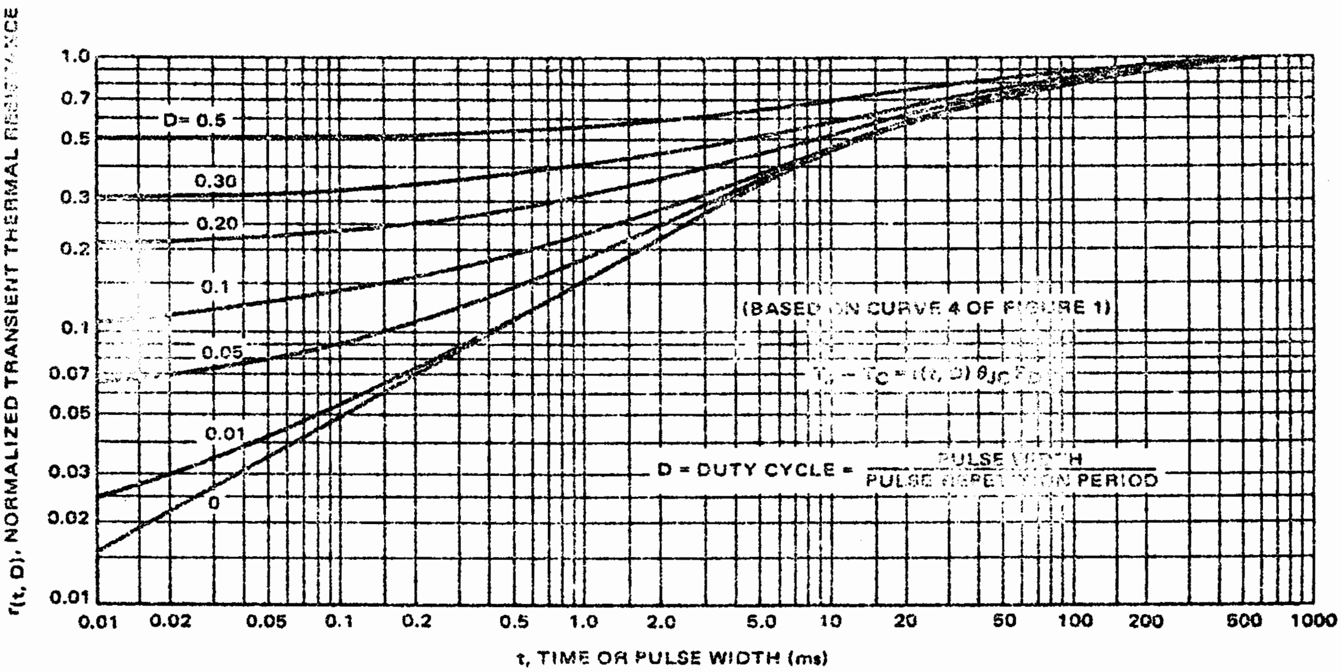

FIGURE 2 – Duty cycle family of curves for a selected transistor.

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

$D = t/\tau_p = 5/20 = 0.25$. 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 $D = 0.3$ curves. At 5 ms, read $r(t,D) = 0.45$.

$$T_J = 0.45 \times 35 \times 5 + 75 = 79 + 75 = 154^{\circ}C$$

The average junction temperature increase above ambient is:

$$\begin{aligned} T_{J(average)} - T_C &= \theta_{JC}\,P_D\,D \\ &= (35)(5)(0.25) \\ &= 43.75^{\circ}C \end{aligned} \qquad (3)$$

Note that T_J at the end of any power pulse does not equal the sum of the average temperature rise (43.75°C in the example) and that due to one pulse (57.8°C in example), because cooling occurs between the power pulses.

If the temperatures calculated are lower than $T_{J(max)}$, the device should operate satisfactorily providing the load line of operation is within the safe area. Safe area should always be checked. As a rule of thumb for pulses of power shorter than 1 ms, second breakdown limits power at low reference temperatures while thermal resistance limits power at high temperatures.

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.

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_0, 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 1 under Method 1.

For uniform trains of repetitive pulses, better answers and less work is required by averaging the power pulses to achieve an average power pulse and then calculating the temperature at the end of the n or n+1 pulse. The essence of this method is shown in Figure 6. The duty cycle family of curves shown on 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 1 shows equations for calculating the temperature at the end of the nth or n+1 pulse in a uniform train. Where a duty cycle family of curves is available, of 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.

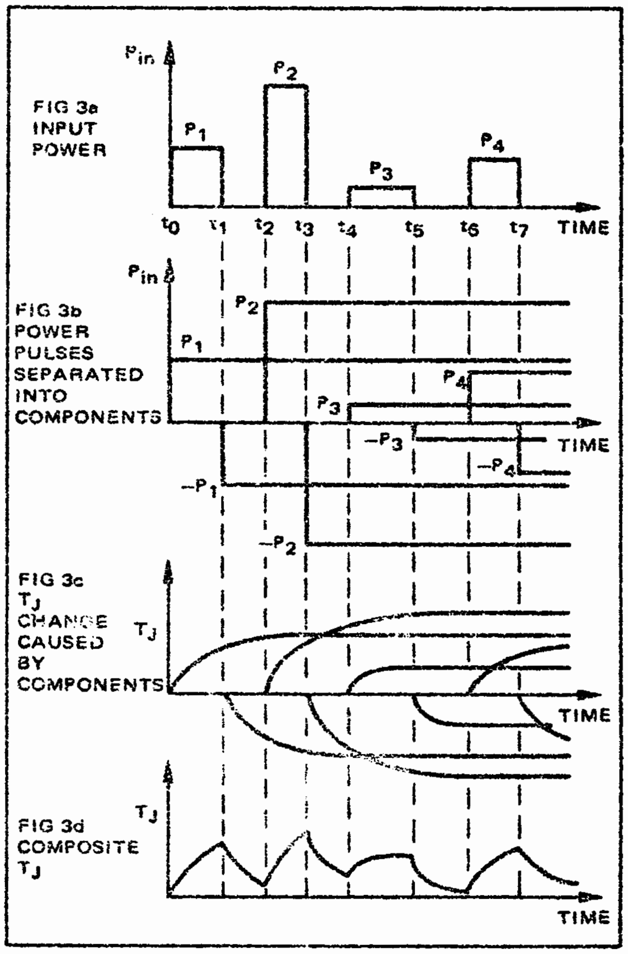

FIGURE 3 – Application of superposition principle

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 3rd 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.

For a power 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, can be proven to be a conservative model (see Figure 7a). For a triangular or sine-wave power pulse, as shown in Figure 7b, a model with an amplitude equal to 70% of the peak and a width of 70% of the actual width has been found to yield results close to the actual case. Power pulses having more complex waveforms could be modeled by using two or more pulses as shown in Figure 7c.

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:

Device = 2N3716

$\theta_{JC} = 1.2°C/W$, $I_C = 10$ A, $V_{CE} = 80$ V

$t_f = t_r = 1\ \mu s$, $t_{off} = t_{on} = 4\ \mu s$, $\therefore \tau = 10\ \mu s$

$P_{on} = 20$ W, $P_{fp} = P_{rp} = 200$ W

(Curve 2, Figure 1 applies to the 2N3716)

Procedure: Average each pulse over the period using equation 1-3 (Appendix 1), i.e.,

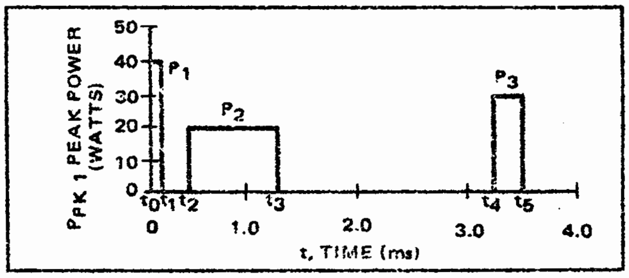

FIGURE 4 – Non-repetitive pulse train
(Values shown apply to example in Appendix I)

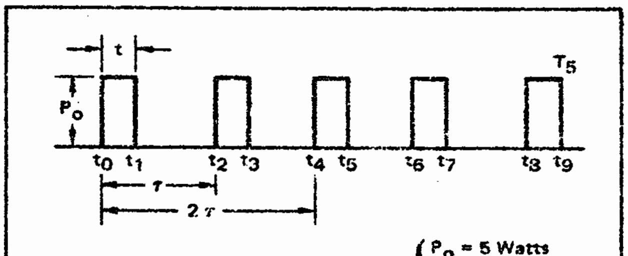

FIGURE 5 – A train of equal repetitive pulses

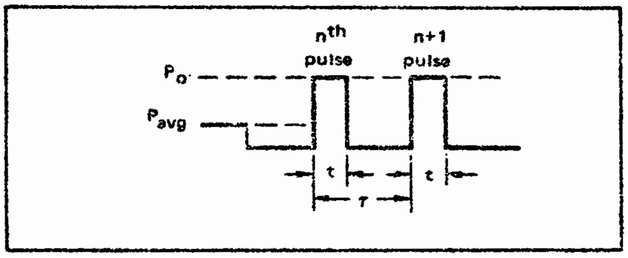

FIGURE 6 – Model for a repetitive equal pulse train

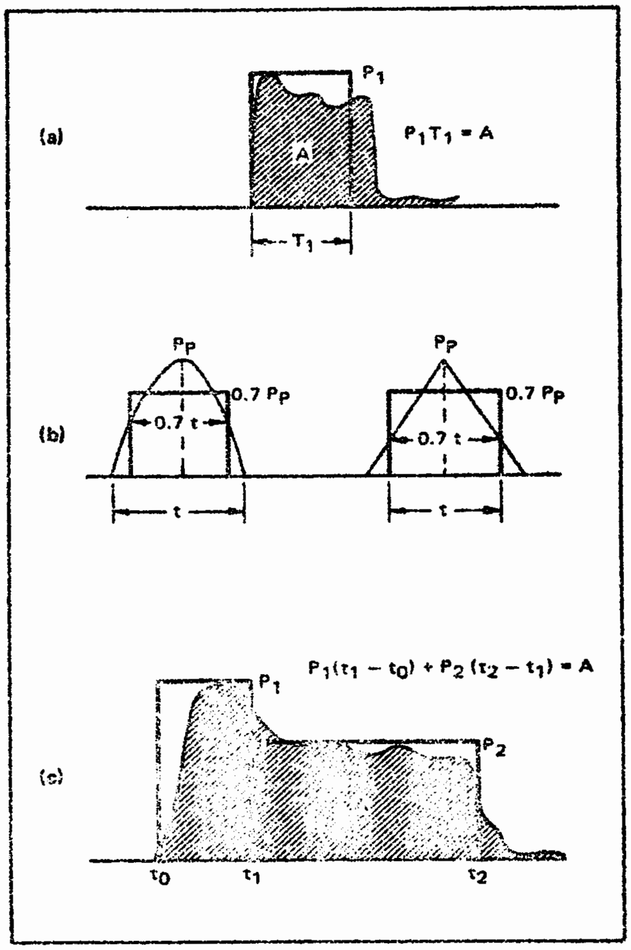

FIGURE 7 – Modeling of power pulses

$$P_{avg} = 0.7\,P_{rp}\,\frac{t_r}{T} + 0.7\,P_{fp}\,\frac{t_f}{T} + P_{on}\,\frac{t_{on}}{T}$$

$$= 140\,\frac{0.7}{10} + 140\,\frac{0.7}{10} + 20\,\frac{4}{10} = 27.6\ \text{W}$$

From equation 1-4, Appendix 1,

$$T_1 = [P_{avg} + (0.7\,P_{rp} - P_{avg}) \cdot r(t_1 - t_0)]\theta_{JC}$$

$r(t_1 - t_0)$ is found from Curve 2, Figure 1

At this point it is observed that the thermal response curves of Figure 1 do not extend to a shorter time than 10 μs because of measurement difficulty. However, indications are that the response curve follows the $\sqrt{t}$ law in this region.

The value for $r(t_1 - t_0)$ or $r(0.7\ \mu s)$ is 0.0085.

We then have:

$$T_1 = [27.6 + (140 - 27.6)\,0.0085]\ 1.2$$
$$T_1 = [27.6 + 0.955]\ 1.2 = 34.3^{\circ}C$$

For T_2 we have by using superposition:

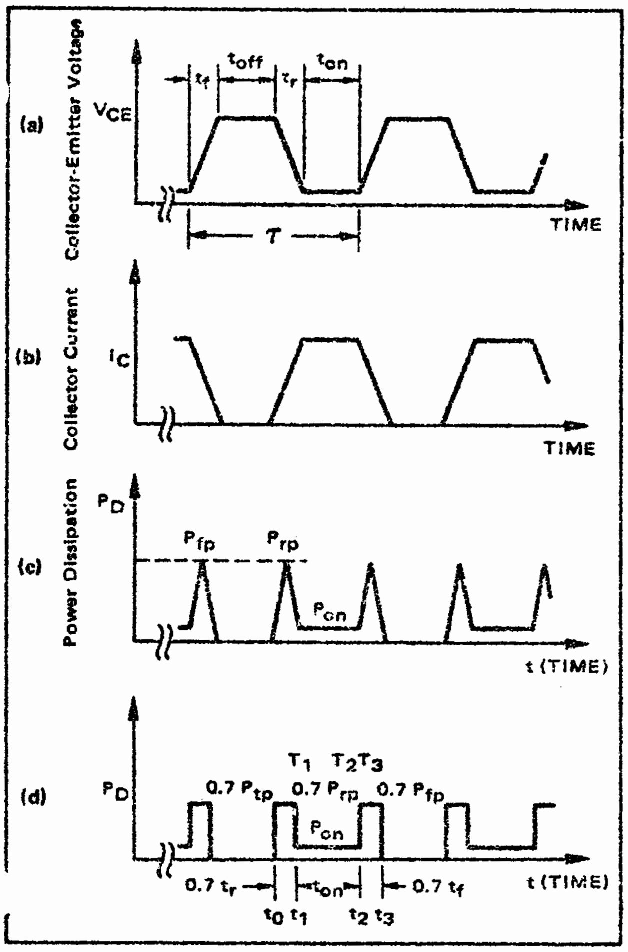

FIGURE 8 – Idealized waveforms of I_C, V_{CE} and P_D in a dc to ac inverter

$$T_2 = [P_{avg} - P_{avg}\,r(t_2 - t_0) + 0.7\,P_{rp}\,r(t_2 + t_0)$$
$$-0.7\,P_{rp}\,r(t_2 - t_1) + P_{on}\,r(t_2 - t_1)]\,\theta_{JC}$$
$$= [P_{avg} + 0.7\,P_{rp} = P_{avg}\ \ r(t_2 - t_0)$$
$$+ P_{on}\,r(t_2 - t_1) - 0.7\,P_{rp}\,r(t_2 - t_1)]\,\theta_{JC}$$
$$= [27.6 + (140 - 27.6)\,0.18 + 20 \cdot 0.017$$
$$- 140 \cdot 0.017]\ 1.2$$
$$= [27.6 + 2.03 + 0.24 - 2.38]\ 1.2 = 33^{\circ}C$$

For the final point T_3 we have

$$T_3 = [P_{avg} - P_{avg}\,r(t_3 - t_0) + 0.7\,P_{rp}\,r(t_3 - t_0)$$
$$- 0.7\,P_{rp}\,r(t_3 - t_1) + P_{on}\,r(t_3 - t_1)$$
$$- P_{on}\,r(t_3 - t_2) + 0.7\,P_{rf}\,r(t_3 - t_2)]\,\theta_{JC}$$
$$= [27.6 - 27.6 \cdot 0.0195 + 140 \cdot 0.0195$$
$$- 140 \cdot 0.0180 + 20 \cdot 0.0180 - 20 \cdot 0.0085$$
$$+ 140 \cdot 0.0085]\ 1.2$$

$$T_3 = [27.6 - 0.538 + 2.73 - 2.52 + 0.36 - 0.170$$
$$+ 1.19]\ 1.2 = 28.65 \cdot 1.2 = 34.4^{\circ}C$$

Inspection of the results of the calculations T_1, T_2, and T_3 reveals that the term of significance is the average power. One might conclude that when a combination of high duty cycle and short pulse widths are present, the product of average power and the steady state thermal resistance is the determining factor for junction temperature rise.

At low duty cycles, the switching losses may produce high peak temperature while the average temperature could be quite low. Slow-speed transistors should be checked for this condition.

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 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 is hot enough to trigger second breakdown.

APPENDIX 1 METHODS OF SOLUTION

In the examples, a type 2N3467 transistor will be used; its steady state thermal resistance, θ_{JC}, is 35°C/W and its value for r(t) is shown by curve 4 in Figure 1.

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:

$$T_n = \sum_{i=1}^{n} P_i \left[r(t_{2n-1} - t_{2i-2}) - r(t_{2n-1} - t_{2i-1}) \right] \theta_{JC} \quad (1\text{-}1)$$

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:

$$T_1 = P_1\, r(t_1)\, \theta_{JC} \quad (1\text{-}1A)$$

$$T_2 = [P_1\, r(t_3) - P_1\, r(t_3 - t_1) + P_2\, r(t_3 - t_2)]\, \theta_{JC} \quad (1\text{-}1B)$$

$$T_3 = [P_1\, r(t_5) - P_1\, r(t_5 - t_1) + P_2\, r(t_5 - t_2) - P_2\, r(t_5 - t_3) + P_3\, r(t_5 - t_4)]\, \theta_{JC} \quad (1\text{-}1C)$$

Example:

Conditions are shown on 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	

Procedure:

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

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

$$T_2 = [P_1\, r(t_3) - P_1\, r(t_3 - t_1) + P_2\, r(t_3 - t_2)]\, \theta_{JC}$$
$$= [40\,(0.175) - 40\,(0.170) + 20\,(0.155)]\ 35$$
$$= [40\,(0.175 - 0.170) + 20\,(0.155)]\ 35$$
$$= [0.2 + 3.1]\ 35 = 115.5^{\circ}C$$

$$T_3 = [P_1\, r(t_5) - P_1\, r(t_5 - t_1) + P_2\, r(t_5 - t_2) - P_2\, r(t_5 - t_3) + P_3\, r(t_5 - t_4)]\, \theta_{JC}$$

$$T_3 = [40\,(0.28) - 40\,(0.277) + 20\,(0.275) - 20\,(0.227) + 30\,(0.07)]\ 35$$
$$= [40\,(0.28 - 0.277) + 20\,(0.275 - 0.227) + 30\,(0.07)]\ 35$$
$$= [0.12 + 0.96 + 2.1]^{\dagger}\ 35 = 3.18 \cdot 35 = 111.3^{\circ}C$$

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.

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

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:

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

Expanding:

$$\begin{aligned} T_n = P_D\,\theta_{JC}\; & r[(n-1)\,\tau + t] - r[(n-1)\,\tau] \\ & + r[(n-2)\,\tau + t] - r[(n-2)\,\tau] + r[(n-3)\,\tau + t] \\ & - r[(n-3)\,\tau] + \ldots + r[(n-i)\,\tau + t] \\ & - r[(n-i)\,\tau] \ldots\ldots + r(t)] \end{aligned} \qquad (1\text{-}2A)$$

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

$$\begin{aligned} T_5 = P_D\,\theta_{JC}\; & [r(4\tau + t) - r(4\tau) + r(3\tau + t) \\ & - r(3\tau) + r(2\tau + t) - r(2\tau) + r(\tau + t) \\ & - r(\tau) + r(t)] \end{aligned}$$

Example:

Conditions are shown on Figure 5 substituting values into the preceeding expression:

$$\begin{aligned} T_5 = (5)\,(35)\; & [r(4\cdot 20 + 5) - r(4\cdot 20) + r(3\cdot 20 + 5) \\ & + r(3\cdot 20) + r(2\cdot 20 + 5) - r(2\cdot 20) + r(20 + 5) \\ & - r(20) + r(5)] \end{aligned}$$

$$\begin{aligned} T_5 = (5)(35)\; & [0.6 - 0.76 + 0.73 - 0.72 + 0.68 \\ & - 0.66 + 0.59 - 0.55 + 0.33] = (5)(35)(0.40) \end{aligned}$$

$$T_5 = 70.0^\circ C$$

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:

$$P_{avg} = P_D\,\frac{t}{\tau} \qquad (1\text{-}3)$$

METHOD 2A – FINDING TEMPERATURE AT THE END OF THE N_{th} PULSE

Applicable Equation:

$$T_n = [P_{avg} + (P_D - P_{avg})\,r(t)]\,\theta_{JC} \qquad (1\text{-}4)$$

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

$$T_n = \left[\frac{t}{\tau} + \left(1 - \frac{t}{\tau}\right) r(t)\right] P_D\,\theta_{JC} \qquad (1\text{-}5)$$

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).

$$\begin{aligned} T_n &= [(1.25) + (5.0 - 1.25)\,(0.33)]\;(35) \\ &= 43.7 + 43.2 = 86.9^\circ C \end{aligned}$$

METHOD 2B – FINDING TEMPERATURE AT THE END OF THE N + 1 PULSE

Applicable Equation:

$$\begin{aligned} T_{n+1} = [& P_{avg} + (P_D - P_{avg})\,r(t + \tau) \\ & + P_D\,r(t) - P_D\,r(\tau)]\,\theta_{JC} \end{aligned} \qquad (1\text{-}6)$$

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

$$T_{n+1} = \left[\frac{t}{\tau} + \left(1 - \frac{t}{\tau}\right) r(t+\tau) + r(t) - r(\tau)\right] P_D\,\theta_{JC} \qquad (1\text{-}7)$$

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).

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

continued

METHOD 2B continued

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+1th pulse. The error occurs because the implied value for T_J at the end of the nth 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 indicates thermal equillibrium 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 N_{th} PULSE FOR PULSES OF EQUAL AMPLITUDE, SPACING AND DURATION

Applicable Equation:

$$T_n = \left[\frac{t}{\tau}\, r\, t_{(2n-1)} + \left(1 - \frac{t}{\tau}\right) r(t)\right] P_D\, \theta_{JC} \qquad (1\text{-}8)$$

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 no cooling time was allowed between P_{avg} and the nth 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

Applicable Equation:

$$T_{n+1} = \left[\frac{t}{\tau}\, r(t_{2n-1}) + \left(1 - \frac{t}{\tau}\right) r(t+\tau) + r(t) - r(\tau)\right] P_D\, \theta_{JC} \qquad (1\text{-}9)$$

Example: Conditions as shown on 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 N_{th} 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.

Applicable Equations:

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

For 3 Pulses:

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

continued

METHOD 3C continued

Example: Conditions are shown on 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

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

$$= 7.88 \text{ Watts}$$

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

$$T_3 = [7.88\,(0.28) + (30 - 7.88) \cdot 0.07]\; 35$$

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

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.,

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

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

TABLE 2 – Summary Of Numerical Solutions For The Repetitive Pulse Train Of Figure 5

Temperature Desired	Temperature Obtained, °C (Method Used)		
	Pulse by Pulse	Average Power, N_{th} 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.

TABLE 3 – Curve Identification, Die Size, And Package (See Figure 1 of Text)

2N Number	Curve Number	Die Size (Mils)	Package
2N1724	3	150 x 150	TO-61
25	3		
2N2192	4		
93	4		
94	4	35 x 35	TO-39
95	4		
2N2217	6		
18,A	6	20 x 20	TO-5
19,A	6		
2N2904,A	6	25 x 25	TO-5
05,A	6		
2N3021	1		
22	1		
23	1		
24	1	60 x 60	TO-3
25	1		
26	1		
2N3055	2		
2N3232	2	120 x 140	TO-3
2N3235	2		
2N3244	4	40 x 40	TO-39
45	4		
2N3252	4	35 x 35	TO-39
53	4		
2N3444	4	35 x 35	TO-39
2N3445	3		
46	3		
47	3	150 x 150	TO-3
48	3		
2N3467	4	40 x 40	TO-39
68	4		
2N3487	3		
88	3		
89	3		
90	3	150 x 150	TO-61
91	3		
92	3		
2N3498	4		
99	4		
2N3500	4	35 x 35	TO-39
3501	4		
2N3506	5	60 x 60	TO-39
07	5		
2N3634	4		
35	4		
36	4	40 x 40	TO-39
37	4		
2N3713	2		
14	2	120 x 140	TO-3
15	2		
16	2		
2N3719	7	60 x 60	TO-39
20	7		
2N3743	5	25 x 25	TO-39
2N3789	2		
90	2	150 x 150	TO-3
91	2		
92	2		
2N4907	2		
08	2	150 x 150	TO-3
09	2		
MJ2255	2		
56	2	120 x 140	TO-3
57	2		
MJ2267	2	150 x 150	TO-3
68	2		
MJ2801	2	120 x 140	TO-3
02	2		
MJ2901	2	150 x 150	TO-3

To measure the thermal response of a transistor, a temperature sensitive parameter of the device is the best 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 the collector-base junction, when operated at 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 suitable for finding the response is shown in Figure 1. With the transistor under test in the circuit, the power-sense switch (SW2) is set in the sense position which removes the emitter current supply and the base return from the transistor. With the collector supply set at a suitable value, the sense supply is adjusted so that a sense current through the base collector junction, just sufficient to bring the forward drop into a fairly linear position of its V-I characteristic, is obtained. The switch is then set to the power position, and the emitter supply is connected. The power can now be applied by opening SW1, which turns on Q1, permitting Q2 and Q3 to turn on, thereby completing the power circuit for the transistor under test.

Power is increased by increasing emitter current until the voltage change of the collector-base junction, when SW1 is thrown to the measure position, is sufficient for accurate readings. Usually about 100 mV is adequate, and several pictures, using different sweep rates, are taken of the response display on an oscilloscope. The thermal response curve is plotted from the photographs.

Power must be supplied to the transistor under test for a sufficient amount of time to insure that the collector-base junction temperature has stabilized. Also, care should be taken that the transistor is mounted on a heat sink in such a way that the case is 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, results will be influenced by the response of the heatsink.

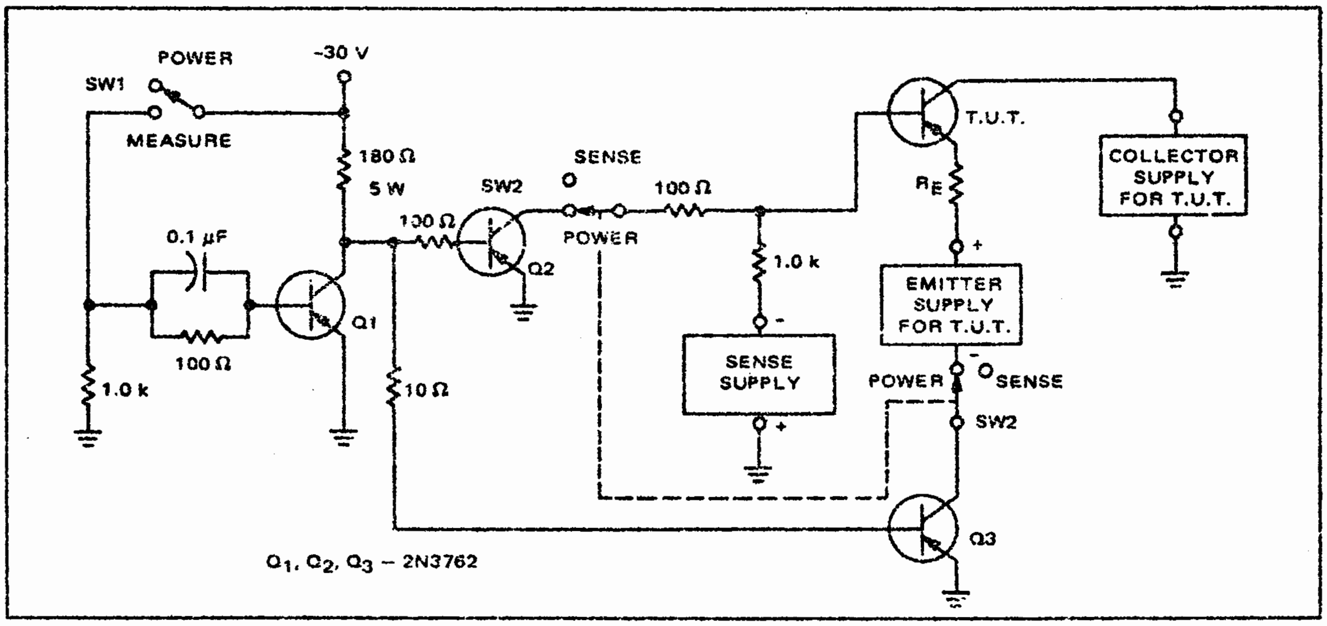

FIGURE 1 – Thermal response test fixture for PNP transistors up to 1 Ampere I_C. A fixture for NPN transistors is built using NPN compliments of the transistors shown and reversing all power supply polarities. The circuit can be scaled up to handle higher currents.

REFERENCES

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