International Rectifier

Application Note **AN-1033**

CALCULATING TEMPERATURE GRADIENTS IN POWER MOSFETS WITH THE “HEXRISE™” PROGRAM

by Doug Butchers, International Rectifier GB Ltd.

(HEXRISE™ may be downloaded from: ***www.irgb.co.uk)***

INTRODUCTION
This note is intended to assist with the application of the Program “HEXRISE™” in practical real life cases.

To use this Program effectively it is important to appreciate its scope and to be able to apply it to thermal calculations for heat sinking arrangements that extend beyond just the immediate boundaries of the power semiconductor itself.

Semiconductor cooling

A typical cooling arrangement for a power semiconductor device will involve the transfer of heat from its source (the junction) through many different materials and interfaces to the final cooling medium - usually air. Along the way, the generation of the temperature gradient of the junction above the ambient temperature, is a function of both the power flow and the thermal response to the different materials encountered in its course.
Figure 1 shows a typical mechanical arrangement for a plastic package on a heat sink. In many cases it would be usual to have an additional isolation layer between the base of the power semiconductor and the heat sink –especially for connections requiring multiple devices.

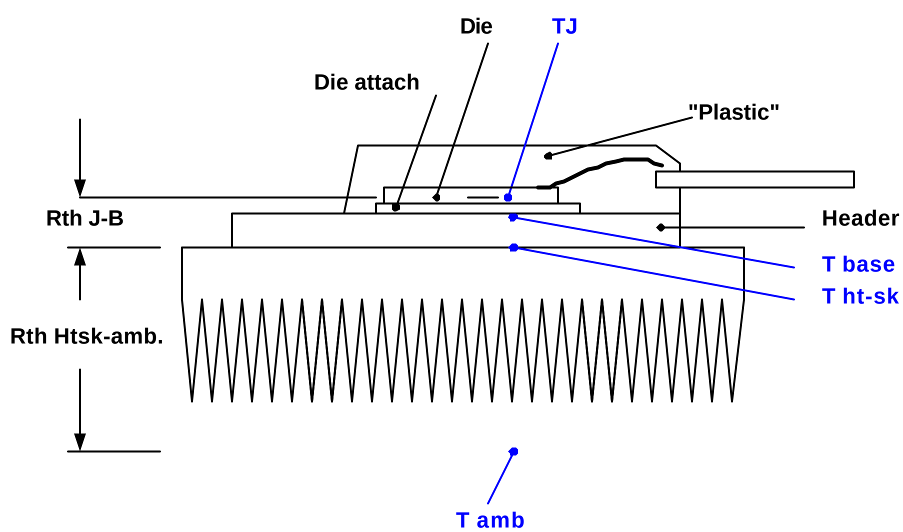


Figure 1: Typical heat sink arrangement

Equivalent thermal circuit

Figure 2 shows an equivalent thermal circuit for the previous mechanical example with the power semiconductor having two significant thermal components-the die and the package header.
There are two parameters associated with each different material section in the thermal path:

1. A thermal resistive element, Rth in K/W
2. A thermal capacity element, Cth in Ws/g.K

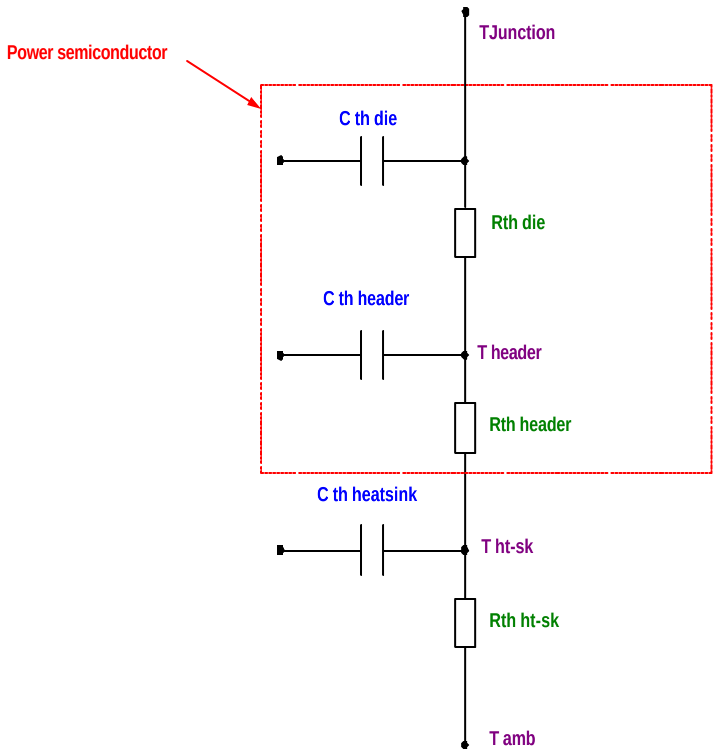


Figure 2: Equivalent thermal circuit

The thermal resistance element is responsible for the steady-state temperature difference across the section in question while the thermal capacity element is responsible for storing heat energy at a given rate, thereby introducing a time function which delays the establishing thermal gradient.
The combination of these two elements has a direct analogy to an electrical circuit containing resistance and capacitance. The Rth x Cth product is the thermal time constant with similar properties to the electrical time constant.

Alternative thermal approach

With HEXRISE™, the thermal response characteristics of the semiconductor is modelled in a more easily accessible way than above. The device thermal parameters (steady–state and transient) are derived from the data sheet transient resistance characteristic - readily available from every device data sheet. (more in the following section.)
Also, unlike the equivalent thermal circuit, the use of the data sheet thermal resistance characteristics makes a knowledge of the **separate** die and header thermal performance parameters unnecessary since the curve reflects the true transient and steady-state performance of the composite packaged part.

Basic Program principles

The temperature rise for a given thermal path in response to a power step such as that shown in figure 3, is given by:

Temp rise @ t1 = P1 x Rth1

Where: P1 the power
Rth1 is the thermal resistance @ time t1

The temperature rise @ t2 = P1 x Rth2 – P1 x Rth1

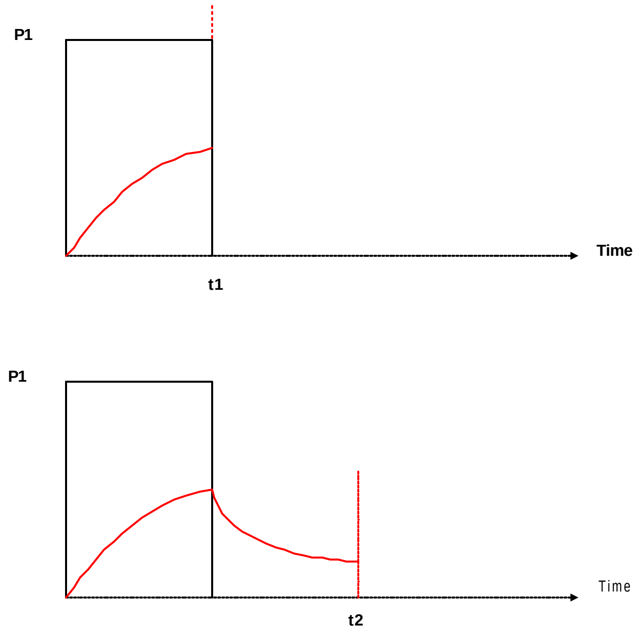


Figure 3: Basic temperature rise calculation

Any current waveform may be approximated by subdividing it up into small sections of time and specifying each subdivision with a power value and a thermal resistance value appropriate to the time at which it occurs. Refer to figure 4.
In this way, the temperature rise at any time may be calculated by applying this principle of positive and negative power pulse contributions to describe the complete wave shape.

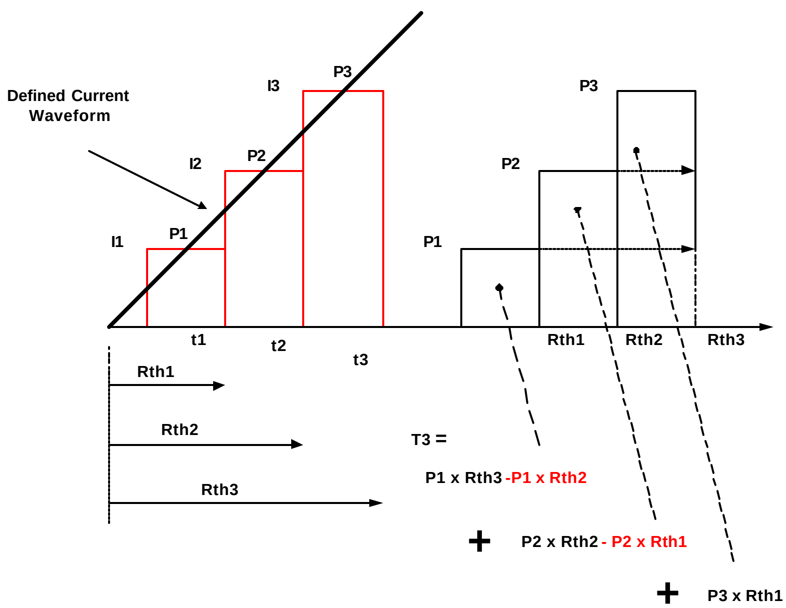
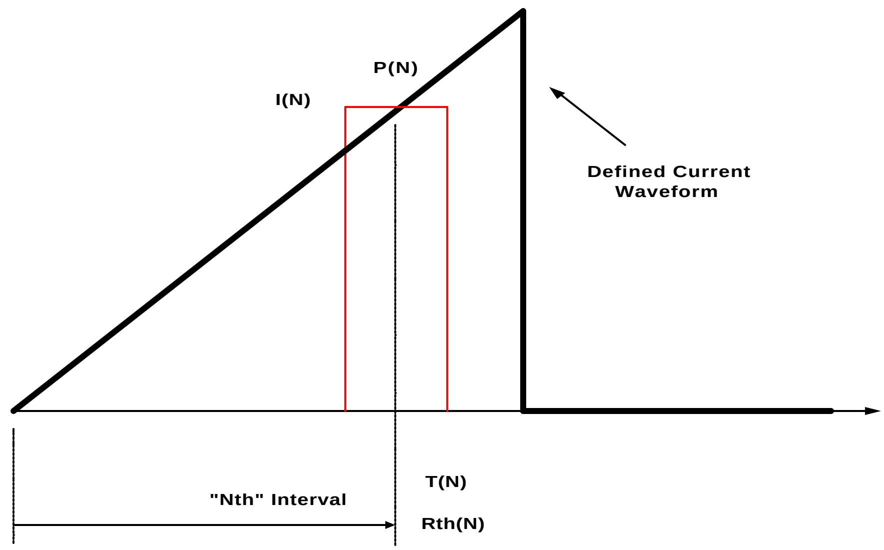


Figure 4: Waveform subdivision

General temperature rise expression

The temperature rise for the complete waveform can consequently be defined by a mathematical series such as that shown in figure 5. Note it is necessary to be able define the current waveform in terms of time for the purpose of calculating the instantaneous power.



$$T_N = P_1 (R_N - R_{N-1}) + P_2 (R_{N-1} - R_{N-2}) + P_3 (R_{N-2} - R_{N-3}) \ldots\ldots + P_N R_1$$

$T_{(N)}$	***is the temperature rise of the junction at the Nth interval***
$P_{(N)}$	***is the instantaneous power in the device at the Nth interval using the mid-point current value***
$R_{(N)}$	***is the transient thermal resistance (Junction-case) for the time $T_{(N)}$***

Figure 5: General series expression

Thermal resistance relationship

HEXRISE uses the transient thermal resistance characteristic from the device data sheet and relates it to time with the expression:

$$R\,(t) = XT \times T^{YT}$$

Where: $YT = \log(R1/R2) / (\log(T1/T2)$

$$XT = R / T^{YT}$$

Note that this calculation will only be valid for calculation times up to the "transient" characteristic limit indicated by the end of the **"straight line"** (Tlim) section of the published thermal resistance curve. Figure 6.

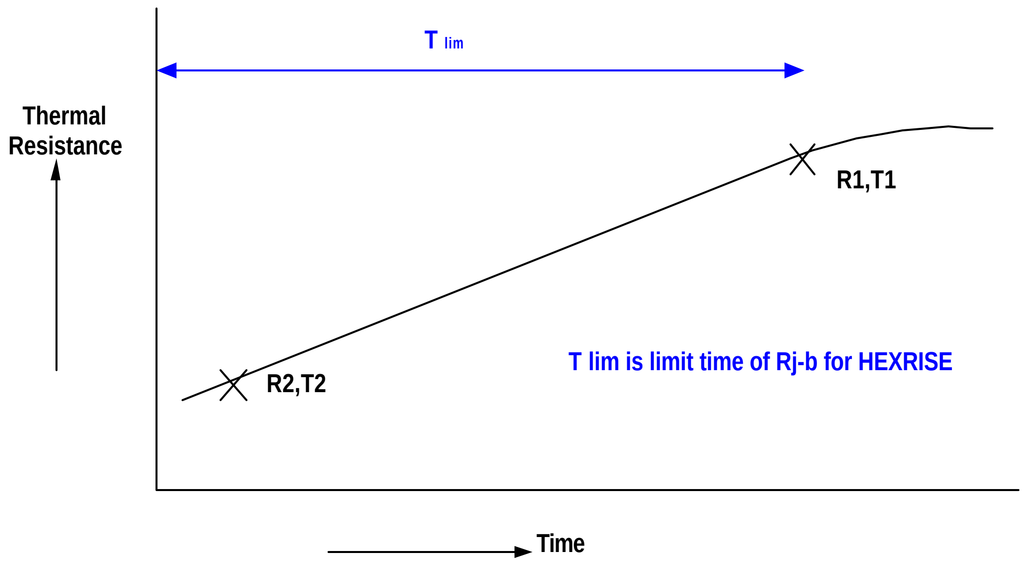


Figure 6: Data book thermal resistance curve (Log/Log scale)

Therefore for a defined current wave shape the temperature rise at a given time may be computed.

Program procedures

The Program computes as follows:

Calculates constants to express thermal resistance as a function of time
(XT and YT)

Creates an array of thermal resistance values for each waveform
subdivision (R_1 to R_N) and one of thermal resistance difference terms, (R_N - R_{N-1}) for the number of time intervals chosen.

Calculates instantaneous power values at each current / time subdivision of the waveform using the current expression as defined by the user. (P_1 to P_N)

Creates an array of Power x Thermal resistance difference terms for "N" time intervals (P_1 x (R_N –R_{N-1})) to (P_N x R_1)

Sums all of the terms for temperature rise for each time interval. Refer to general expression in figure 5.

Using HEXRISE Ô beyond the transient thermal resistance "limit"

The calculation is only accurate for calculation times up to the "transient" characteristic limit indicated by the end of the "straight line" (Tlim) section of the published thermal resistance curve. This can be the key area for accurate calculation as the junction-to-case thermal response is short compared with most heat sink response times and damage can occur to the silicon in these short times.

The HEXRISE™ program provides a means of accurately predicting the short-term temperature rise profile of the MOSFET (Junction-base) during this phase and can provide significant confidence in the long term reliability and integrity of the part in application.

In many applications the complete profile of the semiconductor's absolute temperature depends upon the performance of the other heatsinking. Here it can be important to fully utilise both the steady-state and the transient thermal resistances of these coolers.
For example HEXRISE can also be usefully applied to longer-term high frequency application cases. Here the junction heating and cooling times are shorter in duration and the junction temperature *excursions* are smaller but the average power may well be relatively large. A significant temperature gradient may be developed across the cooling heatsink.

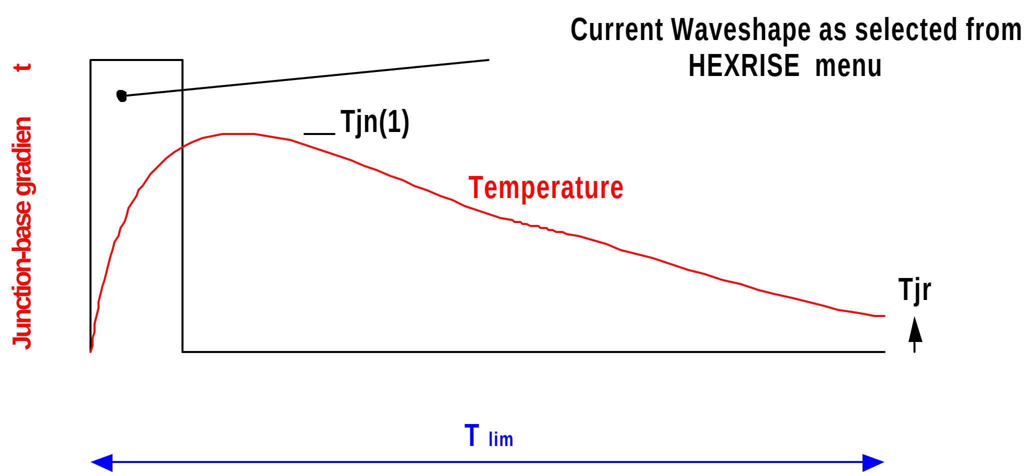
For continuous waveforms use the approach detailed in Application "profile 4" (next section) and run a 10-cycle calculation extrapolating it to a final settled value. This will provide an estimate for the maximum junction temperature excursion.
For a continuous high frequency waveform it will also be necessary to include switching losses and by adding these averaged power losses to the total losses and applying them to the heatsink gradient, the effect on the peak junction temperature may be included.

The section following shows how to combine the results from HEXRISE to those calculations where external heat sinking plays an important role.

Typical Application Profiles

Most applications where this Program will be helpful will have load duty cycles, which are characterised by one of the four following formats:

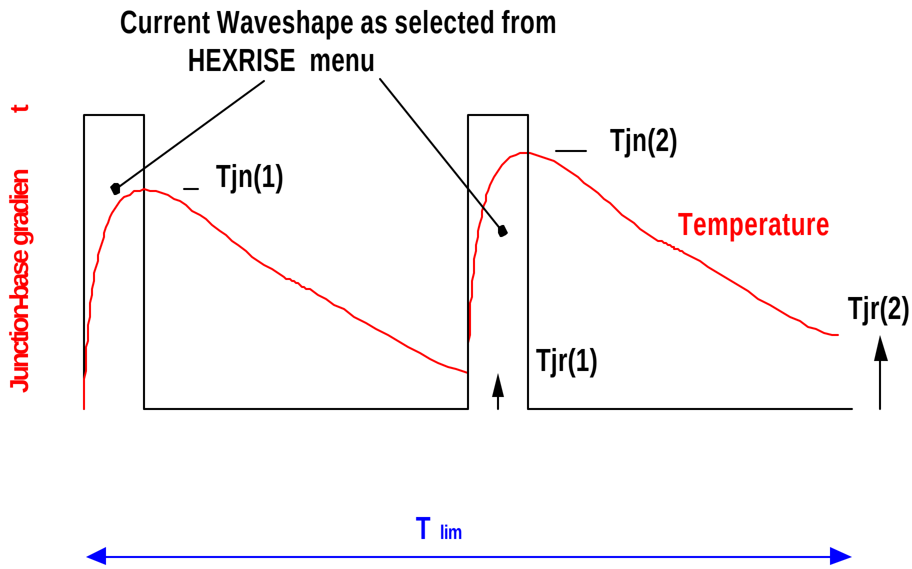
1. ***Single pulse of power within semiconductor transient Rth range (Tlim)***



Key features

- On-time + off-time must be ≤ T lim
- Heatsink (if any) thermal performance is not significant here.
- Maximum absolute junction temperature will be Tjn(1) + starting base / ambient temperature

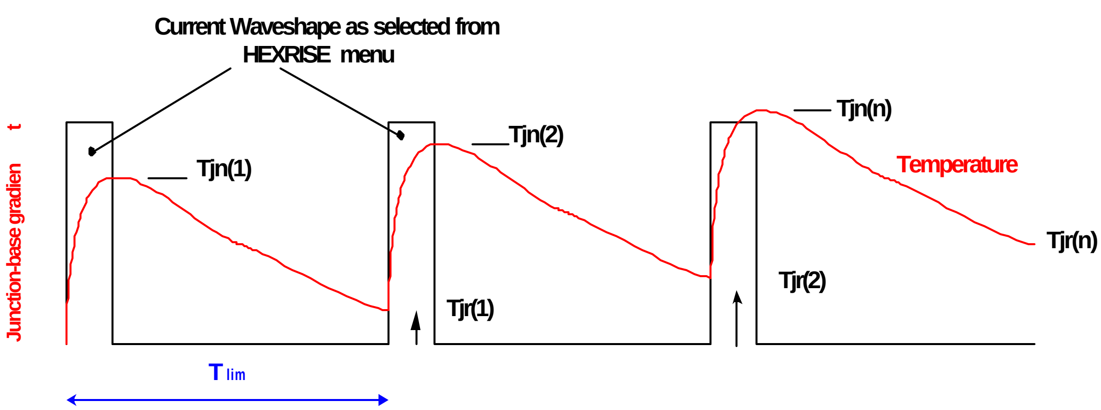
2. Multiple pulses of power within semiconductor transient Rth range (Tlim)



Key features

- Total pulse train time must be T lim
- Each successive peak temperature Tjn(n) and residual cycle temperature Tjr(n) is higher than the one before.
- Heatsink (if any) thermal performance is not significant here.
- Maximum absolute junction temperature will be Tjn(n) + starting base / ambient temperature

3. Multiple pulses of power for time greater than semiconductor transient Rth range (Tlim)



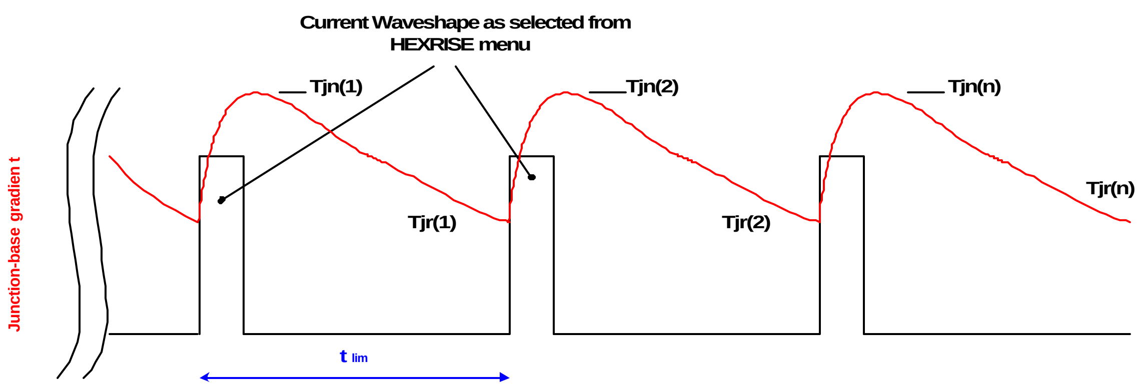
Key features

- Total pulse train time will be $\geq$ T lim
- Each successive peak temperature Tjn(n) and residual cycle temperature Tjr(n) is higher than the one before. A stable (equal) cycle temperature increase and cycle temperature decrease is not achieved.
- Heatsink thermal performance (transient thermal resistance) may be significant here.
- The maximum absolute junction temperature may be estimated for the nth pulse as:-
  $\cong$ (Tjn(n) – Tjr(n)) + W x Rthsk(t) + ambient temperature

  W is the average power dissipated in the heatsink over transient time.

  Rthsk(t) is the heatsink **transient** thermal resistance for time (t) to the nth pulse.

4. Multiple pulses of power for time which achieves steady-state thermal resistance for the heat sink and stable semiconductor temperature cycle increases and decreases.



Key features

- Stable condition exists where Tjn(1)= Tjn(n)
- The maximum absolute junction temperature may be estimated as:

  (Tjn(n) – Tjr(n))** + W x Rthsk(s/s) + ambient temperature

  Rthsk(s/s) is the heat sink steady-state thermal resistance.

  W is the average power dissipated in the heat sink

** Run HEXRISE for sufficient time to be able to identify stability

In all cases considered, the thermal time constant of the heat sink is assumed to be long compared with that of the semiconductor device.

Summary

The junction temperature profile of a power MOSFET for a variety of applied current waveforms may be predicted using the HEXRISEÔ Program.

Short-term temperature effects are calculated directly, while for the longer and continuous events, transient and steady-state temperature rises (determined by relatively large external heatsinks) may be combined with these short-term profiles to arrive at an accurate assessment of the instantaneous junction temperature.

The approach taken in HEXRISE™ very specifically uses data sheet information and thereby deliberately avoids the need for the inclusion of constructional-related details of die and package - not always readily available to the user.

The benefits of being able to assess peak temperature excursions for a variety of applied current waveforms are that reliability and even survivability judgements may be made with some degree of accuracy.

In many applications, such are the economic pressures upon designs, that occasional, severe short-time overloads may have to be accommodated with components whose size or number cannot be increased. A confidence in the maximum temperature peaks and their duration is essential in accurate risk assessment.

HEXRISE™ provides a screen driven format, which enables the user to view the chosen defined current waveform and immediately appreciate the resulting graphical temperature profile.