THERMAL TRANSIENT TESTING HANDBOOK

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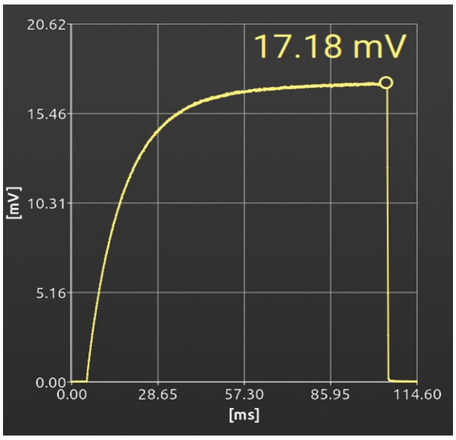
THERMAL TRANSIENT TEST THEORY

The Thermal Transient Test is a non-destructive means for characterizing the bridgewire-explosive interface of an electro-explosive device (EED), also known as an electrically initiated device (EID), detonator, or squib. By applying a controlled current waveform to the device under test (DUT) and examining the signal developed across the bridgewire terminals, the test enables insight into the electrothermal characteristics of the EED.

TEST PROCEDURE

The application of a current to a hot bridgewire type EED induces a rise in bridgewire temperature and an increase in bridgewire ohmic resistance (ΔR). This response allows the characterization of the bridgewire temperature rise using resistance thermometry, provided the bridgewire material temperature coefficient of resistivity (TCR), α, is known.

ELECTROTHERMAL RESPONSE



The adjacent figure illustrates a typical electro-thermal response of an EED under test, as observed on a Pasadena Scientific Industries' Model 730 Thermal Transient Test Set. The waveform's distinctive shape is dictated by the properties of the bridgewire-explosive interface, specifically thermal capacitance and thermal resistance. The initial slope of the curve, determined by thermal capacitance, signifies how rapidly the system responds to the applied thermal stimulus. Conversely, the final amplitude, influenced by thermal resistance, reflects the system's ability to conduct and dissipate heat. Abnormalities at the interface can significantly impact the simplicity of the exponential curve.

INTERPRETATION OF THERMAL RESPONSE CURVES

The interpretation of thermal response curves is vital in understanding the electrothermal characteristics and potential faults within the bridgewire-explosive interface. This includes defects like defective bridgewire welds, bridgewire movement, incorrect compaction pressure, and other irregularities. Each fault category generates a distinctive "signature," making curve interpretation and fault determination a reliable and routine procedure. Representative examples of normal and abnormal thermal response curves, encountered during testing, are provided in the Application Note.

TEST CAPABILITIES

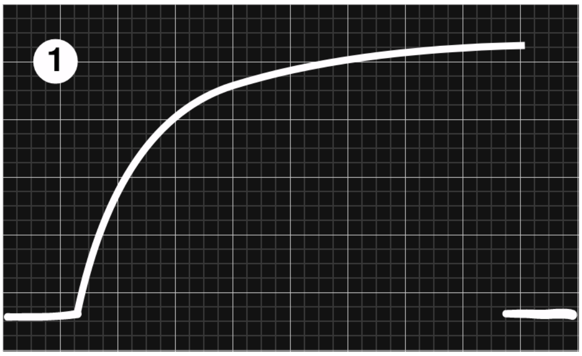
The nondestructive test and measurement capabilities offered by Thermal Transient Testing encompass various aspects of the EED, including:

- Bridgewire weld quality
- Loading density
- Interface air gaps
- Explosive contamination
- Gas inclusion along bridgewire
- Thermal time constant
- Thermal capacity
- Bridgewire resistance
- Bridgewire temperature

Thermal Transient Testing offers a comprehensive and nondestructive approach for inspecting the critical bridgewire-explosive interface, providing valuable insights into the reliability and performance of electro-explosive devices. The interpretation of thermal response curves serves as a key tool in identifying and categorizing faults, contributing to effective quality assurance, development, and production control applications.

Normal Curves

Each EED, when properly fabricated, will generate a thermal response curve whose specific shape is controlled by the thermal capacity and thermal resistance inherent in the design of the EED. A normal heating curve is always smooth and continuous. In addition, normality of the heating curve will depend on its relation to other curves generated by EEDs of the same design in the test population.



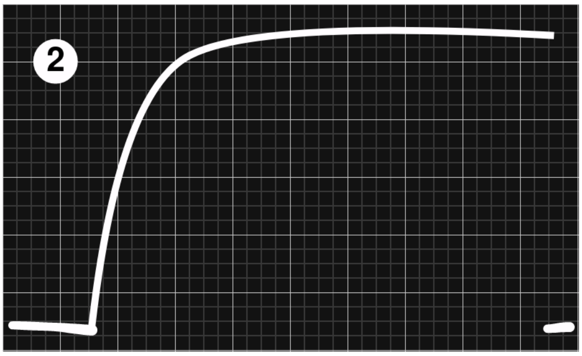
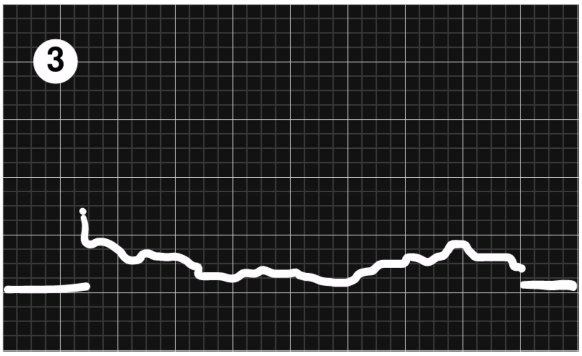
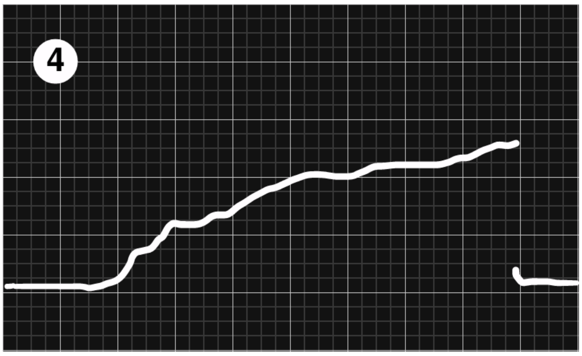


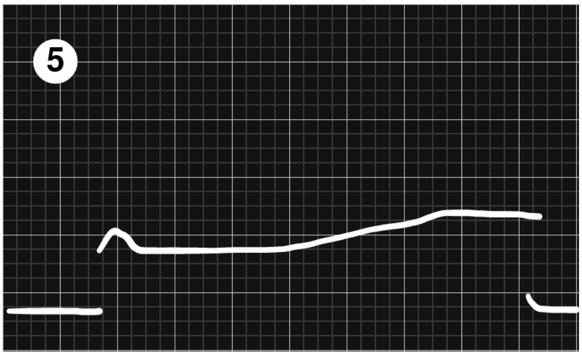
Figure 1 and 2, above, illustrate curves generated by EEDs of two different designs. Each curve is smooth and continuous. In addition, each is assumed to be within acceptable limits relative to other curves in their respective test population. In summary, both curves appear normal in every respect.

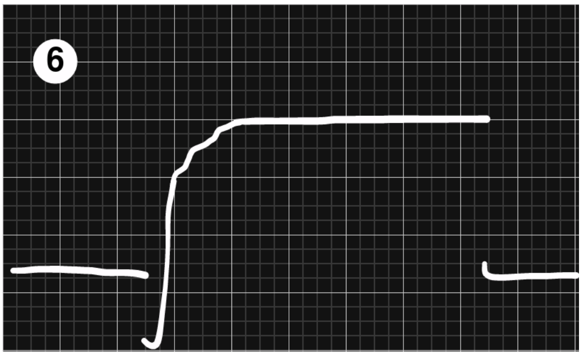
Bridgewire Welds

Defective mechanical fusing of bridgewire and posts, coupled with oxides and semiconductor products at the weld joint, combine to form defective weld. The unstable mechanical and electrical character of defective welds generate a wide variety of erratic responses. Typical responses are shown in Figures 3-6, below. Abnormal welds generally manifest themselves early in the heating cycle (at the onset of the test current pulse).

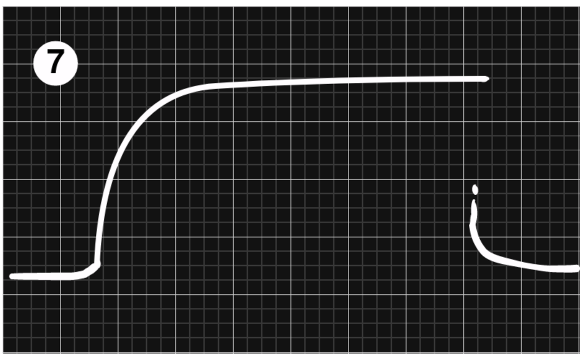


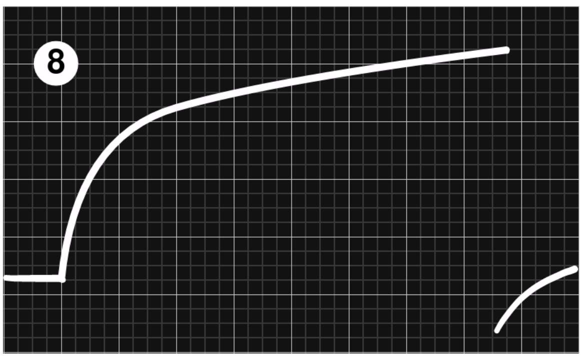






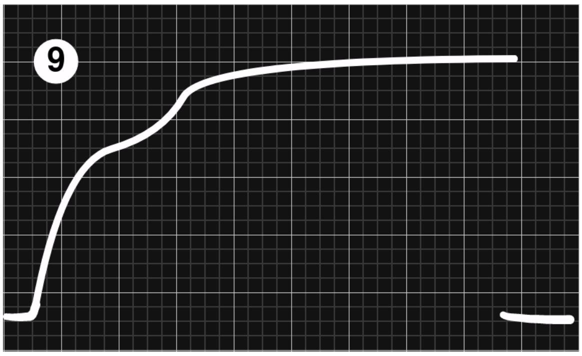
A bridgewire welded to each of the terminals creates a thermocouple junction at each weld. Bridgewire temperature changes generate thermal EMF signals across each weld. If the welds are equal, the two opposing EMF's cancel, with no discernible effect on the heating curve. However, if the welds are different, unequal EMF's generate bridgewire cools to ambient temperature. The decaying residual may be either positive (Figure 7) or, negative (Figure 8). A residual signal may be an abnormality to the extent that it is a possible indicator of a latent weld defect.

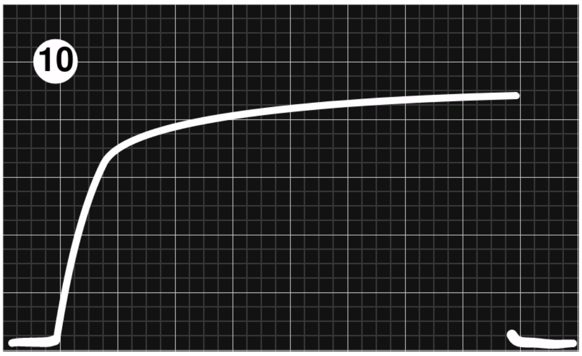




Bridgewire Movement

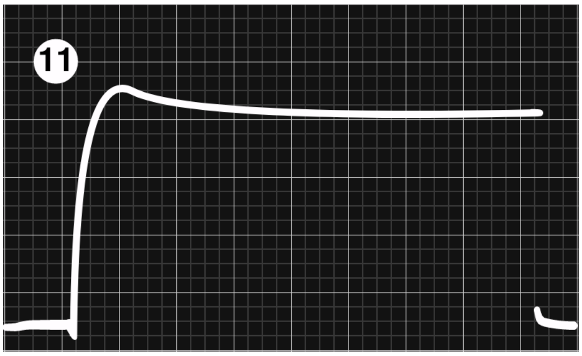
An air gap between the bridgewire and explosive material may permit bridgewire movement as the bridgewire expands and buckles, when heated. As the bridgewire moves, contact is mad with the explosive material causing a change of rate of bridgewire temperature increase, creating a knee in the heating curve. Another potential cause of bridgewire movement is insufficient loading pressure. Bridgewire movement is minimized as the loading pressure may lead to bridgewire burnout before ignition is reached. Curves reflecting bridgewire movement are shown in Figures 9 & 10. Abnormalities related to bridgewire movement are thermally-induced, and occur well into the heating cycle; as indicated in the examples.

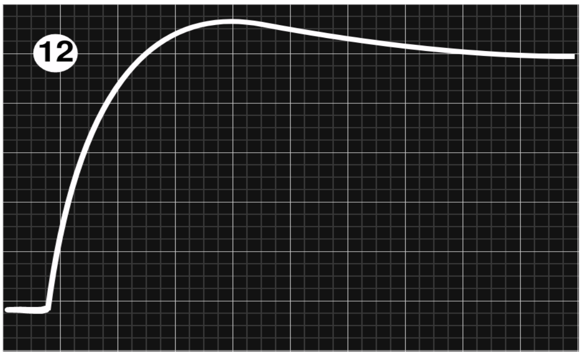




Phase Change

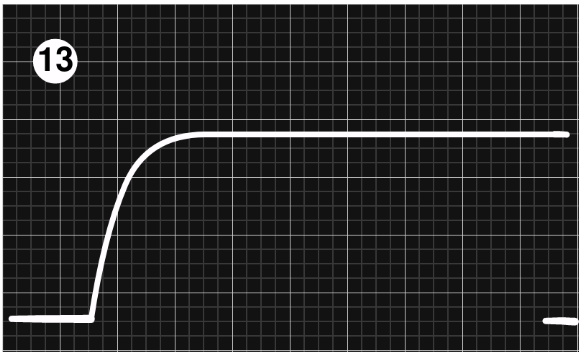
Acetone, MEK, and similar binder solvents, entrapped in explosive mixes can sink appreciable bridgewire heat as the undergo phase change (from liquid to gaseous state) at around 125°C, or so. The cooling effect of residual solvent is indicated in Figure 11, and Figure 12. Cooling starts immediately following the peak of the curves; as the curves begin to fall off. The implications of entrapped solvents are not generally appreciated; however, the condition may seriously affect control of EED sensitivity. It should be noted that the transient test is capable of detecting residual solvents in fully assembled units, as well as partially completed units.

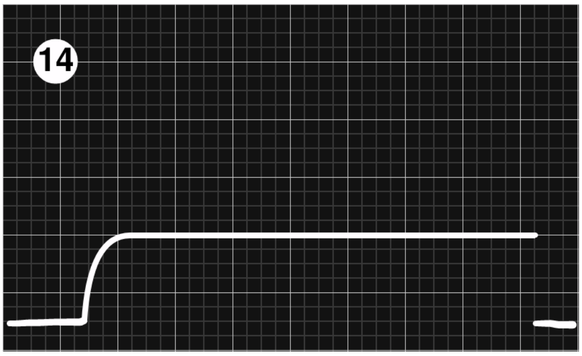




Loading Abnormality

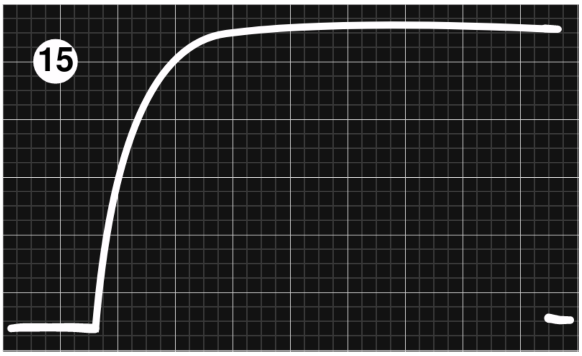
The response of a bridged header without explosive is shown in Figure 13. A device of the same design, with explosive and tested at the same current level, is shown in Figure 14. Neither response is abnormal, as such. The intent is to illustrate the difference due to the absence of explosive. Absence of explosive must be defined as and abnormality in a population of assembled units.

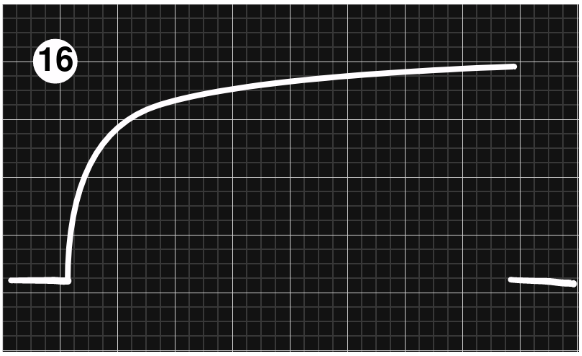




Thermal Stabilization

Temperature rise of the interface tends to stabilize near the end of the primary responses. A component with explosive pressed in intimate contact with bridgewire will display little temperature rise, as in figure 15. An assembly with lesser compaction will exhibit greater rise, shown in Figure 16. Whether a given rise is abnormal or not depends on its relation to other units of the same design in the test population.





Conclusion

The curves described in the preceding pages are typical, basic, and represent those most likely to cause functional problems. Not all possible faults have been covered. One should be alert to the possibility of multiple faults in a single test item. Items exhibiting abnormal responses should be viewed with suspicion and culled out. A knowledge of fault mechanism and curve interpretation should lead to improved product reliability, and reduced development and production costs.

CALCULATION OF ELECTROTHERMAL PARAMETERS

The thermal transient test provides quantitative data for calculation of interface thermal parameters, i.e. thermal conductance, thermal time constants, thermal capacitance, and bridgewire temperature rise. Data for the mathematical calculations are obtained from the test apparatus. Bridgewire material temperature coefficient of resistivity (TCR), α, is obtained from handbook tables, manufacturer's data, or by experimental methods.

Test theory assumes that the interface electro-thermal response, generated by the current waveform, is an exponential. On this bases, Rosenthal[1] derived equations to calculate the electrothermal parameters. Actual testing of loaded units shows the waveform to deviate from a true exponential. However, Rosenthal's equations are used since the primary object of the test is to compare units rather than obtain absolute values.

The thermal parameters are calculated from the expressions below, where:

ΔV_{max} = maximum voltage change at bridgewire terminals
Θ = temperature rise of bridgewire
I = test current
R_o = cold resistance (ohms) of bridgewire
α = temperature coefficient of resistivity of bridgewire
γ = thermal conductance
S = initial slope of heating curve (at t = 0)
C_P = thermal capacitance
τ = thermal time constants
$t_{p\%}$ = time at which the amplitude is equal to p% of ΔV_m value

Treating the bridgewire-explosive interface as a lumped thermal system, we find the differential equation describing the temperature rise (Θ) to be:

$$C_p \frac{d\Theta}{dt} + \gamma\Theta = P(t) \qquad (1)$$

Equivalent heat capacity (C_p) is given in W·s/°C (or J/°C). Simple heat loss is represented by the linear thermal conductance in W/°C. The reciprocal of thermal conductance is thermal resistance, which describes the temperature rise in °C/W dissipation. Power input P(t) as a function of time controls the thermal behavior of the system, and if we select simple P(t) waveform, a recognizable and interpretable response results. The constant current (I) drive resulting in a power

$$P(t) = I^2 R_o (1 + \alpha\Theta)$$

provides a proper, convenient, and easily generated waveform. As the temperature rises, the $\alpha\Theta I^2 R_o$ component corresponds to thermal feedback; regenerative for a positive α.

The solution for (1) is

$$\Theta(t) = \frac{I^2 R_o \left[1 - exp\left(\frac{-\gamma' t}{Cp}\right)\right]}{\gamma'}$$

A maximum temperature rise Θ_{max}, above ambient, at the interface is expressed in °C, and is determined by the definition

$$\Theta_{max} = \frac{\Delta V_{max}}{IR_o\alpha}$$

Thermal conductance γ at the interface is expressed in watts/°C and is determined by the definition

$$\gamma = \frac{\alpha R_o^2 I^3}{\Delta V_{max}}$$

The modified heat loss factor due to feedback is

$$\gamma' = \gamma - I^2 R_o \alpha$$

Thermal capacitance C_P is expressed in watt-seconds/°C is determined by

$$Cp = \frac{\alpha R_o^2 I^3}{S} \qquad \text{or} \qquad Cp = \gamma\tau$$

Thermal time constant τ is expressed in seconds and is determined by the definition

$$\tau = t_{63.2\%} \qquad \text{or} \qquad \tau = \frac{t_{50\%}}{0.69}$$

An apparent time constant is defined as

$$\tau' = \frac{C_P}{\gamma'}$$

This time constant is responsive to the current or power wave form, whereas

$$\tau = \frac{C_P}{\gamma}$$

is intrinsic to the device alone.

The signal, available as a voltage drop $V(t)$ across the bridgewire, is obtained from $V(t) = IR(t)$, where

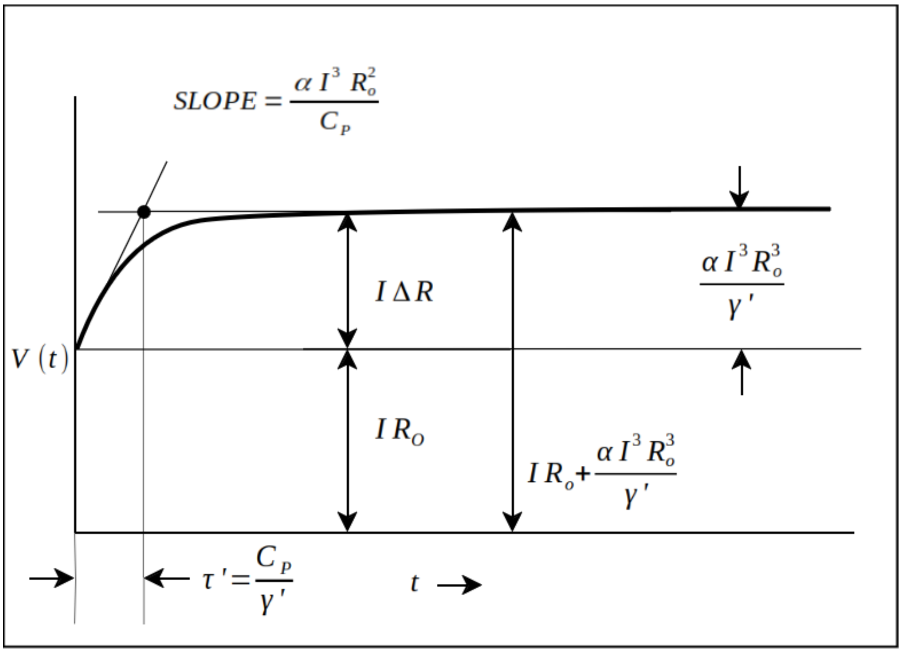
$$R(t) = R_o[1 + \alpha\Theta(t)]. \quad \text{This results in}$$

$$V(t) = IR_o\left\{1 + \frac{\alpha I^2 R_o}{\gamma'}\left[1 - exp\left(\frac{-\gamma' t}{C_P}\right)\right]\right\}$$

It is apparent that the voltage appearing across the bridgewire is a step replica of the current waveform with an exponential rise superimposed as shown in the Figure below. The slope of the exponential portion of the heating curve at t = 0 is

$$SLOPE = \frac{dV(t)}{dt} = \frac{\alpha I^3 R_o^2}{C_P}$$

and can be used to establish C_P/α , a device parameter. Note that the useful signal amplitude is $\alpha I^3 R_o^2/\gamma$ and that it varies with the cube of the current.



[1] L. A Rosenthal, "Electrothermal Equations for Electro-explosive Devices", NAVORD Report 6684, U.S. Navy Ordnance Laboratory, Silver Spring, MD, 15 August 1959.