Thermal Coupling Measurement Method

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Heat flow from an embedded heated wire responds to a change in the ambient environment. The wire is part of a self-balancing bridge system and heat flow is measured directly in watts. Steady-state and transient thermal coupling can be measured directly and is an indication of the thermal resistance and diffusivity for the system under study. The method is applied to an aerospace electroexplosive component.

Nomenclature

a = coefficient
A = area
C = specific heat
C_1 = capacitance
H = heat capacity
k = thermal conductivity
l = length
L_1 = inductance
n = odd integer
P = power
R = resistance
T = temperature
TCR = temperature coefficient of resistivity
V = voltage
w = watts
α = diffusivity
Δ = change
ρ = density
θ = thermal resistance
τ = thermal time constant

Introduction

IN studying the thermal behavior of an electroexplosive device, an experimental method for the measurement of heat flow emerged that may find wider application. An electroexplosive device contains a fine wire (bridgewire) embedded in an explosive material and confined in some hardware enclosure. Electrical energy applied to the bridgewire will heat the wire and if the power is sufficient will result in the initiation of the explosive. Heat generated in the wire must propagate through the explosive and the associated hardware ultimately ending up in the ambient environment. The heat transfer path is complex. It may consist of many parallel paths or paths which have thermal discontinuities and an assortment of unusual boundaries. Accidentally or intentionally paths may be opened due to air gaps or material barriers. The mathematical treatment of the problem becomes formidable since in addition to the complex geometry, the thermal parameters for many of the system components are not known.

The performance of the device depends on the thermal coupling of the wire to the entire system. For example an explosive mixture with high thermal diffusivity will rapidly pass the heat out to the hardware walls; the ultimate heat sink. The bridgewire, the connection pins, and the substrate, as a parallel path, divert the heat flow through a useless path. This of course may be a useful concept for desensitizing the explosive device. In certain cases of faulty manufacture, a change in thermal coupling may anticipate a device failure or malfunction.

Thermal coupling is used as the broader sense of thermal resistance in that it includes a time dependent component. For example, the thermal resistance of a system or device would be expressed as degrees/watt dissipation where the temperature differential is between the source and the heat sink. It is the steady-state component of the thermal coupling which is now treated as a thermal resistance. This concept will be further developed in a later section.

The method is an in situ measurement wherein a fine wire acting as a heat source is buried in the system under study. Heat flows out through the various coupling paths to the ambient environment. By perturbing, the total environment or a specific heat sink area, the coupling to the fine wire can be accurately measured by a change in heat flow. The electroexplosive device was naturally amenable to this type of measurement but heat flow study in other complex systems may also be possible. The principle of operation will be described.

Principle of Operation

Consider the one-dimensional heat flow system of Fig. 1.[1] A wire or film resistor embedded at face 1 is connected to a self-balancing bridge. The bridge[2] heats the resistor to some temperature T_1 and keeps it at that preset temperature (and resistance) by automatically supplying the power required. This power can be measured accurately in watts directly. The walls are insulated and the lateral heat flow is zero. A temperature profile exists down the rod and $T_2 < T_1$ at all times. At steady state this temperature profile is linear and the rod has a thermal resistance θ defined as

$$\theta = (T_1 - T_2)/W \quad (1)$$

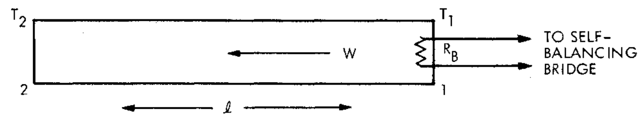

Fig. 1 Simple one-dimensional heat flow model.

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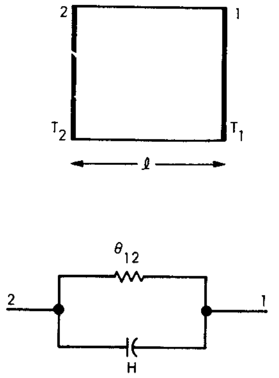

Fig. 2 A lumped thermal model and the resistance-capacitance equivalent.

where W is in watts, T is temperature in °C, and θ is °C/w. The total thermal resistance θ can be related to the thermal conductivity of the rod material k according to

$$\theta = l/kA \tag{2}$$

where length l(cm) and area A(cm^2) refer to the bar geometry and k is the material conductivity in w/°C-cm. Heat is also stored in the heat capacity of the rod material in accordance with the specific heat (C), the density (ρ), the volume, and the temperature (T). The temperature profile results in a corresponding variation in the stored heat.

After steady state is achieved, the end temperature T_2 is elevated (or depressed) by an amount ΔT_2 the heat flow, as measured by W, will change. The transient change will propagate at a rate which depends on the diffusivity, (α) defined as

$$\alpha = k/C\rho \text{ (cm}^2\text{/sec)} \tag{3}$$

where k is the thermal conductivity and $C\rho$ is the heat capacity per unit volume. The lumped system of Fig. 2 passing a heat flux from face 1 to face 2, each of area A, has a thermal resistance

$$\theta_{12} = l/kA \text{ (°C/w)} \tag{3a}$$

and heat capacity

$$H = \rho ClA \text{ (w-sec/°C)} \tag{3b}$$

A thermal time constant τ is introduced as

$$\tau = H\theta \text{ (sec)} \quad = l^2/\alpha \tag{4}$$

or the lumped thermal time constant varies as the length squared and inversely with the diffusivity. The settling down of the transient heat flow terms will take a long time if α is small and path length great.

The lumped model is however inaccurate since the heat capacity must be weighted in accordance with the temperature profile. A distributed heat flow system is best described by an infinite series of time constants[3-5] where

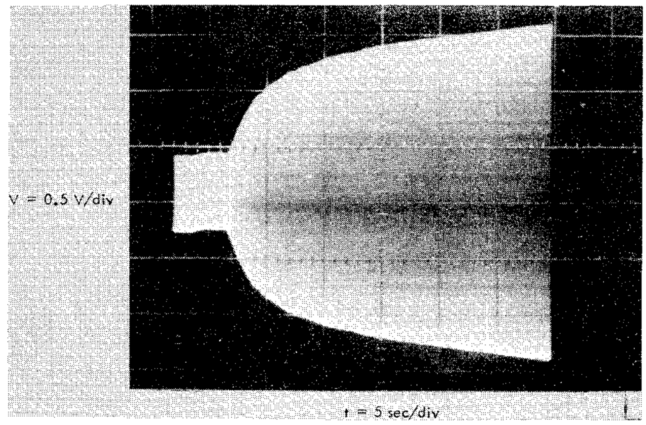

Fig. 4 An oscilloscope display of self-balancing bridge voltage level upon cooling.

$$\tau_n = 4l^2/n^2\pi^2\alpha \quad (n = 1, 3, 5, \ldots) \tag{5}$$

For example, the primary (i.e., longest) time constant ($n = 1$) is 40% ($4/\pi^2$) of the lumped system time constant. The higher order time constants control the heat flow behavior at the beginning of the transient. An expected over-all performance for the experimental system would follow

$$\Delta W = (\Delta T_2/\theta)(1 - \Sigma a_n e^{-t/\tau_n}) \qquad n = 1, 3, \text{etc.} \tag{6}$$

where the summation of exponential terms vanish as time (t) approaches infinity and the final change in power flow (ΔW) is proportional to the perturbation in temperature. The coefficient a_n scales the relative importance of each exponential term.

Diffusivity plays a major role in controlling the transient heat flow, and simple exponential transients are only obtained in lumped models. The general problem of thermal coupling is further complicated by the heat flow not being a single dimensional problem, by many ports of heat entry, and by the terminating thermal impedances (at T_2 and T_1) not being isothermal. However, the experimental procedures and observations can be interpreted in terms of the models proposed and therein lies their value.

Experimental Procedure

The measurement method as employed with an electroexplosive device will demonstrate the procedure. Figure 3 is a typical aerospace electroexplosive device. The bridgewire is buried deep in a complex thermal system and heat flow from the bridgewire can take place along the explosive column, through

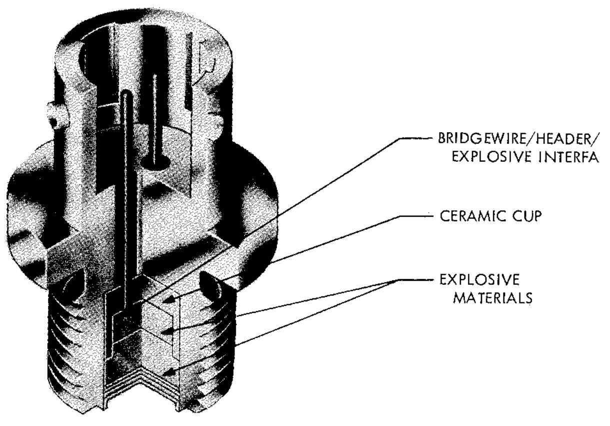

Fig. 3 The typical aerospace electroexplosive device.

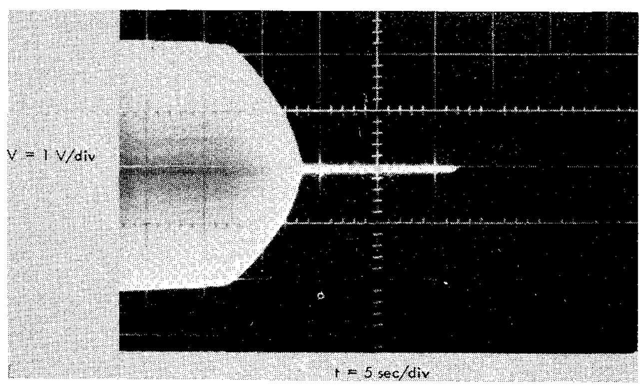

Fig. 5 Heating the environment produces a drop in self-balancing power.

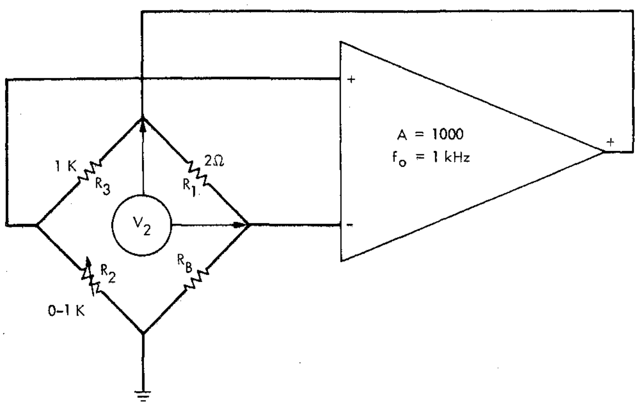

Fig. 6 The self-balancing bridge components.

the ceramic cup and metal hardware, and through the electrical pin connections. Proper electrothermal performance requires that the bridgewire dissipate its heat through the complex coupling paths unless the energy exceeds a critical level. For example, this unit must be capable of continuously dissipating 1 w without firing. For transient inputs, the thermal diffusivity controls the performance since an impulsive input can heat the bridgewire up to the ignition point before heat propagates out to the device walls.

Heat flow starts from the wire and in a three-dimensional pattern flows out to the device walls as an ultimate heat sink. The preferred or dominant paths might be considered one dimensional except in the immediate vicinity of the bridgewire. By employing the bridgewire in a self-balancing bridge, the wire can be raised a few degrees above ambient (i.e., the device walls) and the power flowing into the wire measured directly. Naturally the temperature of the bridgewire must be maintained at a safe low level, far below that experienced in firing the device. At an equilibrium condition, the entire device can be inserted into a hot or cold bath to provide a + or $-\Delta T_2$. The heat flow (w) pattern is upset and at a rate determined by the diffusivity, a new equilibrium condition is obtained. Instead of isothermal perturbation, it is possible to utilize a heated airjet and direct the thermal disturbance along a specific port of entry.

A display obtained from an oscilloscope is shown in Fig. 4 for the case of $-\Delta T_2$ (or cooling). This trace is reducible to power flowing into the bridge and is the amplitude of the 1000 Hz self-balancing bridge. The bridge will be described in a later section. At the start the power level in the bridgewire is small and constant. Roughly 5 sec after the start of the display, the entire unit was inserted into a water bath at 0°C. Depressing the sink environment resulted in an increased flow of heat (as measured in watts) from the bridgewire out to the sink. This thermal coupling has a response time of several seconds and at the end of the trace (i.e., 30 sec) equilibrium has not been achieved. The envelope is proportional to a voltage (or current) and the power follows the square of the display amplitude. At the end of the trace the power dissipation in the bridgewire is 17 mw for an item that is capable of safely passing 1 w at steady state.

If from any initial level, the device experiences a $+\Delta T_2$ for the heat sink environment, less heat is propagated out of the bridgewire and the amplitude decays in the manner shown in Fig. 5. At

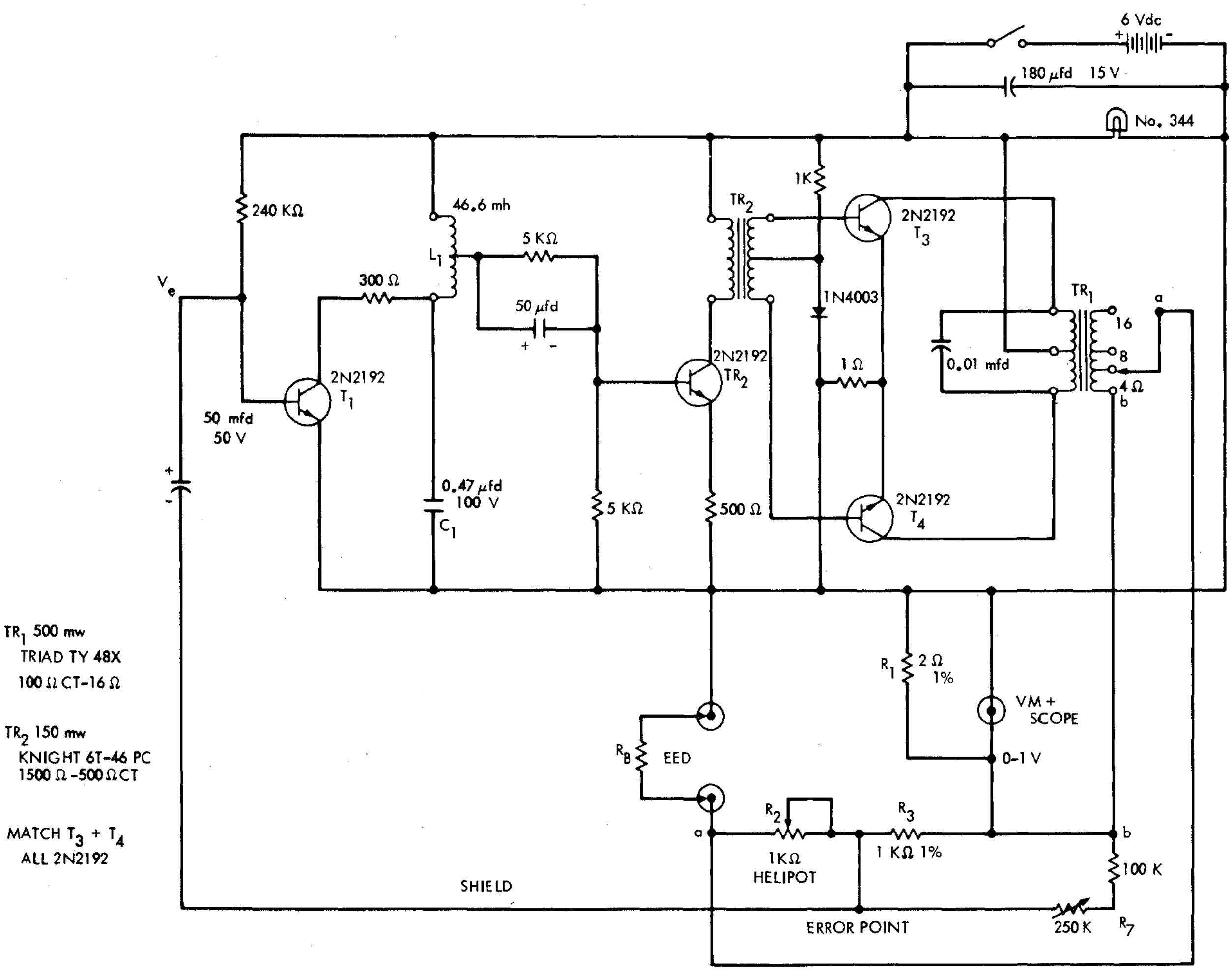

Fig. 7 The detailed schematic of a self-balancing bridge for electro-explosive devices.

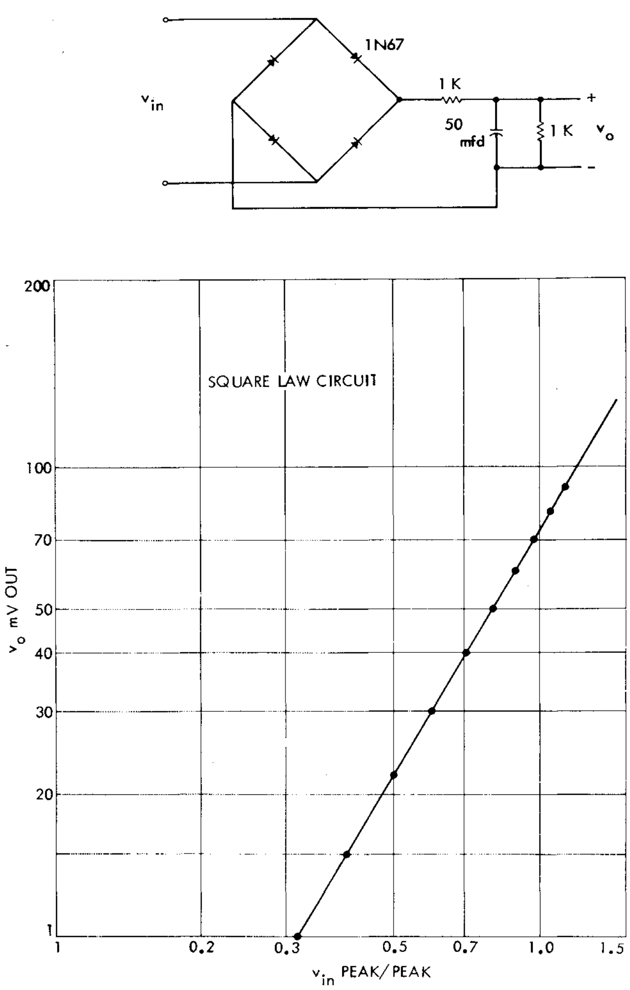

Fig. 8 Diode bridge square law circuit.

a critical level, the heat flowing into the device equals that flowing out and there is no longer any need for self-balancing power. The circuit stops oscillating abruptly at a level that depends on the start point power. At all times heat must flow out of the bridgewire for proper action. The basic principle of the self-balancing bridge will be presented.

Self-Balancing Bridges

The circuit shown in Fig. 6 includes the essential components of a self-balancing bridge system. Resistor R_B is a positive temperature coefficient of resistance element that will increase its resistance due to self heating. For the electroexplosive devices under study it is a fine nichrome wire with a nominal resistance of 1.0 ohm. Feedback arms R_1 and R_B provide degeneration whereas arms R_2 and R_3 provide the positive feedback for self-oscillation. The differential input amplifier with a nominal gain of 1000 is selective at 1000 Hz. If R_2 is set to unbalance the bridge, oscillation will take place, heating the resistor R_B up to a near balance condition. Perfect balance can never be achieved but a high gain (i.e., 1000) could easily bring R_B to 0.2% of the set point. Calling for a higher operating resistance will require higher power inputs and the drop out level corresponds to the bridge being balanced with no power input (i.e., at ambient temperatures). Reference 2 treats the theory and application of self-balancing bridges more thoroughly. The power dissipated in the resistor R_B can be determined by measuring the voltage drop V_2 across the R_1 resistor (i.e., 2Ω) according to

$$\text{Power} = V_2^2 R_B / R_1^2 \tag{7}$$

Setting R_B via R_2 is equivalent to selecting the temperature at some constant value. As external power is injected into R_B it can be measured as a change (decrease) in the self-balancing power according to

$$P_{\text{ext}} = (V_2^2 - V_2'^2) R_B / R_1^2 \tag{8}$$

where V_2 and V_2' are the initial and final voltage readings across R_1. Similarly if heat is withdrawn from R_B by improved heat sinking then the sign of P_{ext} will be reversed and the self-balancing power will be increased. The measurement of radiation and microwave power are typical well established techniques employing self-balancing bridges and in these cases the R_B resistor is a bolometer. Foils and films are other geometries which can be employed for R_B; the constant temperature sensor.

The complete circuit diagram of the self-balancing bridge employed in these studies is shown in Fig. 7. Power output is derived from the push-pull class B stage and the proper output transformer tap. Saturation clipping limits the maximum power output to about 40 mw for a 1 ohm bridgewire and calculations show that the corresponding temperature rise would be only 7°C above ambient for the system studied. Error signal derived from the bridge is returned to T_1 acting as a selective amplifier based on the selection of $L_1 - C_1$. The inductor is center tapped to reduce the loading of stage T_2 which is the push-pull driver. Excellent balancing action is obtained with a loop gain slightly over 1000. The entire unit is powered by a 6-v battery which supplies the maximum current required of 150 ma.

A vernier resistor combination (R_7) allows for fine adjustment of the R_B set point (i.e., $\frac{1}{3}$%–1% and hence a convenient initial power level. The external VTVM (0–1 v) and 'scope across the 2Ω (R_1) resistor insure that the circuit is operating properly. The voltmeter reading can be converted to power in a simple manner. Resistance connections to R_B must be secure and rigid. For example with a tophet "A" material of $TCR = 100 \times 10^{-6}$ per °C at a 1 ohm level 100 μΩ change are equivalent to 1°C change of R_B temperature. As shown, the 1000Ω helipot (R_2) is capable of selecting a set point of 0 to 2Ω and each division is 2 m ohms resulting in a coarse control. Upon installing R_B and increasing R_2, an oscillation break in point is reached. The vernier can be adjusted to set the power to an appropriate level. Touching the item walls will result in an equivalent ΔT_2 and must be avoided.

Rather than depend on an oscilloscope trace for the response plots, a simple square law detector driving a strip chart recorder was employed as an improved system. For the bridge rectifier circuit shown in Fig. 8a employing point contact diodes, an approximate square law characteristic results (Fig. 8b). The 100 mv maximum output signal is applied directly to a strip chart recorder (Hewlett-Packard Model 680) and power can be read directly according to

$$\text{Power} = 0.45 \times 10^{-3} V_o$$

In this equation the recorded voltage V_o is in millivolts d.c. The calibration is based on a 1 ohm device resistance level and the converter circuit is always placed across the 2 ohm resistor which monitors the self-balancing current. The convenience of recording power directly is obvious. Some recordings will be shown in the section on typical experimental observations.

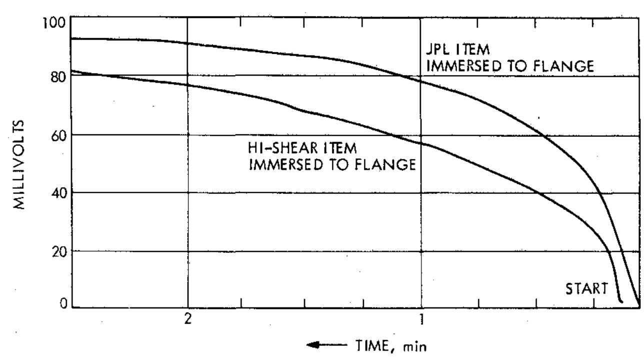

Fig. 9 Observed traces for typical items.

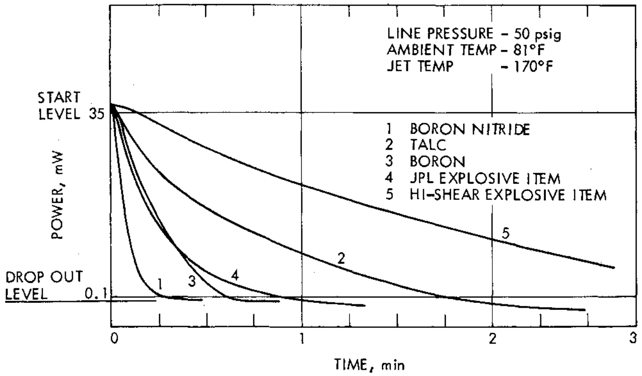

Fig. 10 A comparison of several systems.

Experimental Observations

The thermal coupling measurement provides both a static and transient evaluation for the device under test. Using the square law converter and the strip chart recorder proved to be the most convenient procedure. The item under test is installed in the self-balancing bridge and the initial power is selected anticipating a cooling or heating thermal environment. For example in cooling, the initial power level is set close to zero at a level sufficient for sustained oscillation. Upon putting the item in an ice bath, the $-\Delta T_2$ results in an increase in power due to additional heat flow. Figure 9 is typical observed recordings for two aerospace items of different manufacture but made to the same specifications. The item was immersed up to a mounting flange and after $2\frac{1}{2}$ min the heat flow in watts is still increasing. It is obvious that the heat diffusion pattern is different for each of the designs but the asymptote is roughly the same. At equilibrium, the thermal resistance of any device can be determined according to

$$\theta = (T_1 - T_2)/(P_2 - P_1) \; (°\text{C/w}) \tag{9}$$

where P_2 and $P_1 (= 0)$ are the final and initial power levels, respectively, and T_2 (0°C) and T_1 (25°C) are the corresponding environment conditions, respectively. It is obviously not necessary to start at $P_1 = 0$ and based on the set point for the self-balancing bridge, a ΔP can readily be measured.

If the item is immersed in the water bath to a greater depth, the power will change at a faster rate indicating more coupling paths are involved. Little can be said about the shape of the curve but a replot of the data for both cases shown resulted in a variation of the form $P = a(t)^{1/2}$ in the initial regions where "a" is a constant.

Another improved technique is based on the injection of heat along a particular path. A fine jet of heated air† is directed at the output end of the device. A thermal barrier shields the body of the item from the heated jet so that all heat propagation is down the explosive column. Since in this case the environment experiences a $+\Delta T_2$, the self-balancing bridge must feed less heat down the thermal coupling path and the initial level is set at a conveniently higher level (i.e., 35 mw). As heat moves down the explosive, the self-balancing bridge power decreases until the circuit drops out of oscillation.

Figure 10 is a composite plot for a variety of items, all identical in hardware and dimensions, but loaded with different materials and tested by jet heating of the output end. The time to reach the dropout level varies dramatically depending on the column material. Boron nitride (i.e., # 1 see legend on Fig. 10) provided the lowest thermal resistance and the highest diffusivity. Curve # 5 for a manufactured explosive item exhibited a poor diffusivity that was traced to an air gap in the explosive column.

The typical experimental observations have been presented to demonstrate the potential of the measurement method to the testing of electroexplosives. It appears possible to characterize the heat flow behavior response to variations in manufacture, possible internal faults, heat sinking performance, and a variety of similar design studies.

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† Manufactured by Sylvania Emissive Products, Box 220, Exeter, N.H.