N70 35563

NASA CR-[illegible]1

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1494

Nondestructive Testing of Insensitive Electroexplosive Devices by Transient Techniques

L. A. Rosenthal
Rutgers University

V. J. Menichelli
Jet Propulsion Laboratory

CASE FILE
COPY

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

July 15, 1970

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1494

Nondestructive Testing of Insensitive Electroexplosive Devices by Transient Techniques

L. A. Rosenthal
Rutgers University

V. J. Menichelli
Jet Propulsion Laboratory

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

July 15, 1970

Prepared Under Contract No. NAS 7-100
National Aeronautics and Space Administration

Preface

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

Acknowledgment

Thanks are due A. J. Murphy and J. Earnest for encouragement and help and A. Livanos for assistance in assembling apparatus and making measurements.

Contents

Table

Figures

Abstract

By pulsing an electroexplosive device with a safe level constant current and examining the resistance variation of the bridgewire, it is possible to explore the electrothermal behavior of the bridgewire–explosive interface. The bridgewire, acting as a resistance thermometer, provides a signal which describes the average wire temperature and the heat sinking to the explosive and enclosure. This report describes equipment and observations specific to nondestructive testing of 1-W/1-A no-fire devices.

Nondestructive Testing of Insensitive Electroexplosive Devices by Transient Techniques

I. Introduction

A bridgewire in an electroexplosive device is the electrothermal transducer that converts electrical energy input into heat, the object being to reach the initiation temperature at the bridgewire–explosive interface predictably and reliably. The present discussion is concerned with the nondestructive evaluation of this interface and the transducer input circuit. Defects in performance can occur beyond this interface, but it appears that evaluation of the bridgewire region can be most productive in evaluation of unit performance. Certainly, if the explosive–bridgewire interface is reliably evaluated, a true assessment of the other components in the explosive train can result.

The nondestructive test method developed is based on the application of a current pulse to the squib under test and the examination of the voltage developed at the bridgewire terminals.[1] If the bridgewire has some temperature coefficient of resistivity (TCR) α, the signal developed can be related to the bridgewire temperature rise in a manner such as in resistance thermometry. Since the bridgewire has thermal heat sinking to both the explosive and the squib hardware system, the total temperature rise of the bridgewire is a measure of the thermal conductance γ. The rate at which the temperature climbs, observed as a transient change, is directly related to the thermal time constant τ of the system. When a lumped model analysis of the system is employed (Ref. 1), the time constant is equal to the ratio of the equivalent thermal heat capacity C_p to the conductance (i.e., $\tau = C_p/\gamma$).

If the bridgewire has zero TCR, there obviously would be no way of sensing the temperature, and this nondestructive testing system would fail. Similarly, if the TCR varies from unit to unit owing to wire imperfections and manufacturing faults (e.g., solder flow), another error source would be introduced into the measurement. With good assembly techniques these problems should be minimal; however, it is important to have the bridgewire material TCR known in order to relate it to the actual temperature.

The nondestructive aspect and the safety implied are closely related to the TCR. Consider the resistance temperature relationship about an ambient temperature (i.e., 25°C):

$$R_\theta = R_0\,(1 + \alpha\theta) \qquad (1)$$

---

[1] The theory and methodology which are the basis for this work were developed by the Explosion Dynamics Division, U. S. Naval Ordnance Laboratory, White Oak, Md.

The TCR is based on 25°C, and R_0 is the resistance at this temperature. At any temperature, the resistance R_θ varies in a linear manner for any temperature increase θ. The per-unit change in resistance is

$$\frac{(R_\theta - R_0)}{R_0} = \frac{\Delta R}{R_0} = \alpha\theta \tag{2}$$

A detection oscilloscope capable of measuring small voltage changes ΔV senses $\Delta R/R_0$. For example, if $\Delta R/R_0 = 1\%$, an $\alpha = 100 \times 10^{-6}$ would result in a temperature rise during the test of

$$\theta = \frac{0.01}{100 \times 10^{-6}} = 100°\mathrm{C}$$

Because of ignition temperatures for common primary explosives used in electroexplosive devices, it would be considered unsafe to exceed an average temperature of 300°C. Thus, selecting the appropriate test current commensurate with the explosive sensitivity is of paramount importance. Testing at below ambient temperatures can expand the allowable ΔR during test, but this is an inconvenient approach.

II. Basic Theory

Treating the bridgewire–explosive interface as a lumped thermal system, we find the differential equation (Refs. 2–4) describing temperature rise θ to be

$$C_p \frac{d\theta}{dt} + \gamma\theta = P(t) = I^2R_0\,(1 + \alpha\theta) \tag{3}$$

Equivalent heat capacity C_p is given in W-s/deg (or J/deg). Simple heat loss is represented by the linear thermal conductance term γ in W/deg. The reciprocal of thermal conductance is ρ $(1/\gamma)$, the thermal resistance, which describes the temperature rise in deg/W dissipation. Power input $P(t)$ as a function of time controls the thermal behavior of the system, and if we select a simple $P(t)$ waveform, a recognizable and interpretable response results. The constant current I drive resulting in a power

$$P(t) = I^2R_0\,(1 + \alpha\theta) \tag{3a}$$

provides a proper, convenient, and easily generated waveform. As the temperature rises, the $\alpha\theta I^2R_0$ component corresponds to thermal feedback, regenerative for a positive TCR.

The solution for Eq. (3) is

$$\theta(t) = \frac{I^2R_0\left[1 - \exp\left(-\frac{\gamma' t}{C_p}\right)\right]}{\gamma'} \tag{4}$$

The modified heat loss factor due to feedback is

$$\gamma' = \gamma - I^2R_0\alpha \tag{4a}$$

Time constants are defined as

$$\tau' = \frac{C_p}{\gamma'} \tag{4b}$$

These time constants are responsive to the current or power waveform. The equation

$$\tau = \frac{C_p}{\gamma} \tag{4c}$$

is intrinsic to the device alone.

The signal available as a voltage drop $V(t)$ across the element is obtained from

$$V(t) = IR(t)$$

where

$$R(t) = R_0\,[1 + \alpha\theta(t)]$$

This results in

$$V(t) = IR_0\left\{1 + \frac{\alpha I^2R_0}{\gamma'}\left[1 - \exp\left(-\frac{\gamma' t}{C_p}\right)\right]\right\} \tag{5}$$

It is apparent that the signal is a step replica of the current waveform with an exponential rise superimposed as shown in Fig. 1. The slope of the exponential portion at $t = 0$ is

$$\frac{dV(t)}{dt} = \frac{\alpha I^3R_0^2}{C_p} \tag{5a}$$

and can be used to establish C_p/α, a device parameter. If the initial slope is extended until the extended plateau is intersected, the time is the extrinsic time constant

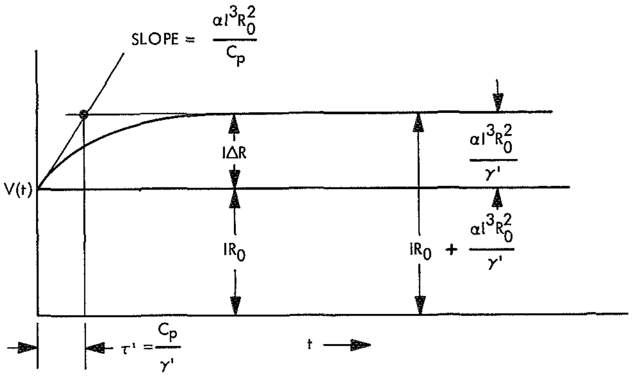


Fig. 1. Voltage drop across the bridgewire

$\tau' = C_p/\gamma'$. Note that the useful signal is $\alpha I^3 R_0^2/\gamma'$ and that it varies with the cube of the current.

From quantitative measurements on this display it is possible to characterize the explosive device in terms of the parameters γ and C_p. If we assume that α is not to be resolved but treated as a reliable constant, the terms γ/α and C_p/α can be equally useful. For example, the exponential increase over the base is $\Delta R/R_0$ or

$$\frac{\Delta R}{R_0} = \frac{\alpha I^2 R_0}{\gamma'} \tag{6}$$

Rearranging terms, we obtain

$$\frac{I^2 R_0}{\left(\frac{\Delta R}{R_0}\right)} = \frac{\gamma'}{\alpha} \tag{6a}$$

which defines a power sensitivity in watts/per unit ohm change and provides a useful classification parameter.

As a better procedure for evaluating the voltage trace, it is possible to model the thermal response behavior with passive electrical components and construct a "transient" Wheatstone bridge circuit. When a step current I is passed through the circuit shown in Fig. 2, a voltage drop $V_1(t)$ results, taking the expression

$$\begin{aligned} V_1(t) &= I_1 R_1 + I_1 R_2 \left(1 - \exp - \frac{t}{R_2 C_2}\right) \\ &= I_1 R_1 \left[1 + \frac{R_2}{R_1}\left(1 - \exp - \frac{t}{R_2 C_2}\right)\right] \end{aligned} \tag{7}$$

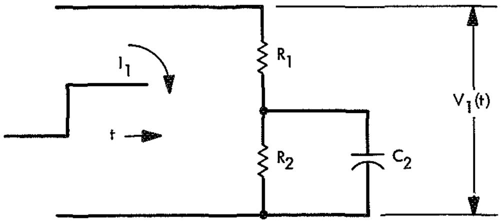


Fig. 2. Electrical model passing a step current

This equation form is identical to that of Eq. (5). For an identical match of waveforms, the following equivalence equations would be required

$$IR_0 = I_1 R_1 \tag{8}$$

$$I_1 R_2 = \frac{\alpha I^3 R_0^2}{\gamma'} \tag{8a}$$

$$\frac{C_p}{\gamma'} = R_2 C_2 \tag{8b}$$

The branch currents (I and I_1) establish the ratio between R_1 and R_0 or the model resistance and the cold resistance of the electroexplosive device. Consider the bridge circuit shown in Fig. 3 with a step applied voltage V as shown. Although the current I is not truly constant, the small change in the squib resistance (i.e., 5%) practically encountered is masked out by the resistor R_A as a ballast. Typically, R_A would be about 10 times R_0, and R_B would be 5×10^4 times R_A (i.e., $R_A = 10\ \Omega$; $R_B = 500 \times 10^3$). With these values of ratio arms, the current in the electrothermal model is $1/50 \times 10^4$ that in the squib arm. Neglecting the reaction of the squib

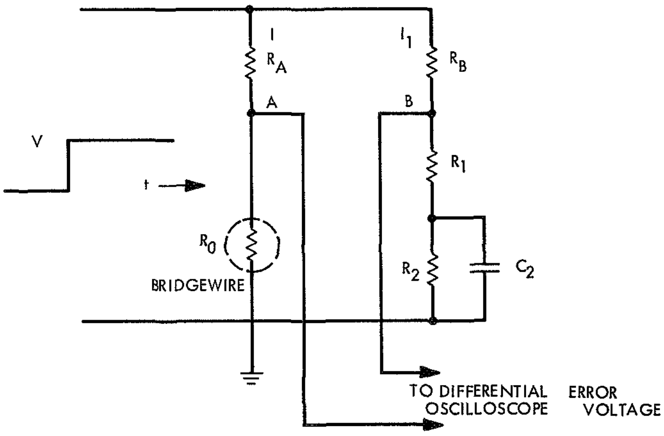


Fig. 3. Bridge circuit used in pulse testing

and model to the voltage source V, we find that the branch currents are

$$I = \frac{V}{(R_A + R_0)} \tag{9}$$

$$I_1 = \frac{V}{(R_B + R_1)} \tag{9a}$$

Combining these current relationships with the balance or matched waveform conditions of Eqs. (8), (8a), and (8b), we obtain the following results:

$$R_0 = \frac{R_A R_1}{R_B} \tag{10}$$

$$\frac{\gamma'}{\alpha} = I^2 R_0 \left(\frac{R_1}{R_2} \right) \tag{10a}$$

Equation (10a) is the more convenient form, and I can be calculated from $V/R_0 + R_A$. Since $\gamma' = \gamma - I^2 R_0 \alpha$, the intrinsic γ can be resolved as

$$\frac{\gamma}{\alpha} = I^2 R_0 \left(1 + \frac{R_1}{R_2} \right) \tag{10b}$$

Note that since R_2/R_1 is equivalent to $\Delta R/R_0$, it is realistic to ignore the one (1) term in Eq. (10b) for 5% changes in R_0. The time constant balance condition is

$$\tau' = C_2 R_2 \tag{10c}$$

Practically, the match of the model to the squib can be accomplished by means of a differential oscilloscope as indicated in Fig. 3. With R_2 and C_2 set at zero, R_1 is adjusted so that the pedestal of waveform A is removed. The voltage at B is a simple rectangular pulse, and this primary balance establishes the cold resistance according to Eq. (10). The net positive going exponential can be dropped below the zero axis by increasing R_2, and the value of R_2 required corresponds to the $\Delta R/R_0$ of the squib or the amplitude of the exponential temperature rise. Introducing C_2 cancels the exponential, and the flattest curve is the best fit. The sequence of waveforms is shown in Fig. 4.

In practice, a square-wave pulse at 5 to 10 pulses/s will provide a repetitive pattern during the balancing procedure. The *on* and *off* time interval must be sufficient for the device to reach thermal equilibrium (i.e., five time constants) when the *on* pulse is terminated; the model (C_2) capacitor stores energy which will appear as a discharge at t_1 (see Fig. 4). Interestingly, the electrothermal process is irreversible, and the stored thermal energy cannot be returned to the circuit.

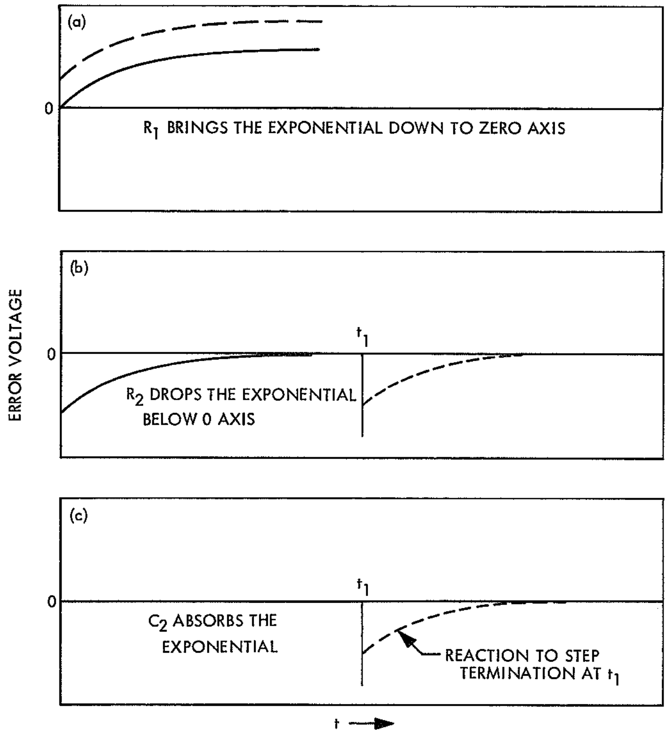


Fig. 4. Steps followed in balancing the model to the squib

In cancelling the time constant parameter or exponential portion, we seek a best fit. Occasionally, there is a residual short time constant attributable to temperature profile redistribution along the wire and extraneous reactances (electrical); it is best ignored. The bridge has only the potential for cancelling out a single time constant, and in the event that a distribution of time constants exists or the temperature rise follows other functions (e.g., Gaussian), only an effective or dominant time constant is resolved. The limit or asymptote of the exponential may also display a long, slow climb typical of a long time constant. This response is typical of thermal transmission through a distributed system of the explosive and housing. It may not be possible to represent this time-dependent phenomenon by a simple additional time constant.

III. The Apparatus

The equipment necessary to perform the indicated tests in a rapid and efficient manner is shown in Fig. 5.

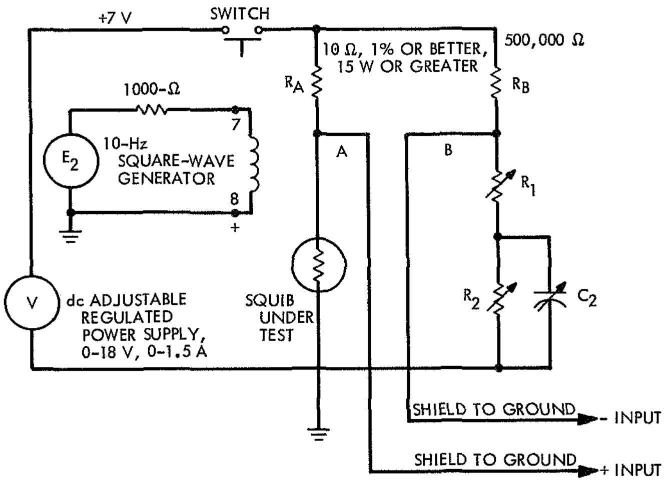


Fig. 5. Circuitry for testing 1-W/1-A electroexplosive devices

Fixed resistors R_A and R_B with accuracies of better than 1% set the ratio arms. Since R_A can dissipate significant power it should be on a thermal heat sink and have a sufficient power rating. Resistor decade boxes make up R_1 (0–100,000 Ω) and R_2 (0–10,000 Ω), while C_2 is a decade capacitor extending up to 10 mF in 0.01-mF increments. An additional fixed capacitor of 10 mF may be desirable for long time constant determinations.

All leads should be shielded and decade boxes grounded to eliminate 60-Hz stray pickup. The bridge error voltages at A and B are subtracted in a differential dc scope of 1-mV/cm sensitivity. Good common mode rejection and equal sensitivities are essential for good performance. High-quality binding posts and connectors should be used in connection with the squib. Since it may be desirable to keep the squib in a firing chamber, high current leads should be employed. A Kelvin-type resistance measurement is preferred in which current leads feed the squib and voltage leads pick up only the voltage drop. Careful control of the residual resistances is required in order to establish an accurate resistance measurement. A standard resistor can be substituted for the squib for test purposes, and except for the exponential portion, the R_0 balance will determine the bridge accuracy.

The voltage source V is a regulated supply and must be able to supply a test current according to $I = V/(10 + R_0)$. Regulation must be both static and dynamic (i.e., transient), since any power supply voltage variations can appear as an error (even at balance). As a safety precaution, a voltage limit to "crowbar" the supply is recommended.

The mercury switch is driven by a square-wave voltage source E_2 at a frequency which allows for approximately five time constants of heating and an equivalent cooling. With a good square-wave drive there is negligible jitter in the closing cycle. By triggering the scope sweep with this signal, the pull-in delay provides for a complete heating cycle. It is, of course, possible to synchronize the scope to the total bridge voltage.

The selection of the bridge voltage is based on the maximum average temperature θ_m that can be tolerated for a nondestructive test and a signal level compatible with the system signal-to-noise ratio. Obviously, the maximum temperature of the profile is the most important constraint. The signal output from Eq. (6) is

$$\Delta V = I \Delta R = \frac{\alpha I^3 R_0^2}{\gamma'}$$

and, from Eq. (4),

$$\theta_m = \frac{I^2 R_0}{\gamma'}$$

Therefore,

$$\Delta V = \alpha I R_0 \theta_m \tag{11}$$

or the per-unit change in voltage is

$$\frac{\Delta V}{I R_0} = \alpha \theta_m \tag{11a}$$

If the current is set on the basis of θ_m, as $I_{\max}(I_m)$,

$$I_m = \left(\frac{\gamma' \theta_m}{R_0} \right)^{1/2}$$

Then

$$\Delta V = \frac{\alpha R_0^2}{\gamma'} \left(\frac{\gamma' \theta_m}{R_0} \right)^{3/2}$$

$$= \alpha \, (R_0 \gamma')^{1/2} \, \theta_m{}^{3/2} \tag{11b}$$

The fact that the signal varies as the current cubed is of greatest importance, since levels should be set primarily on the basis of a good, clean output signal.

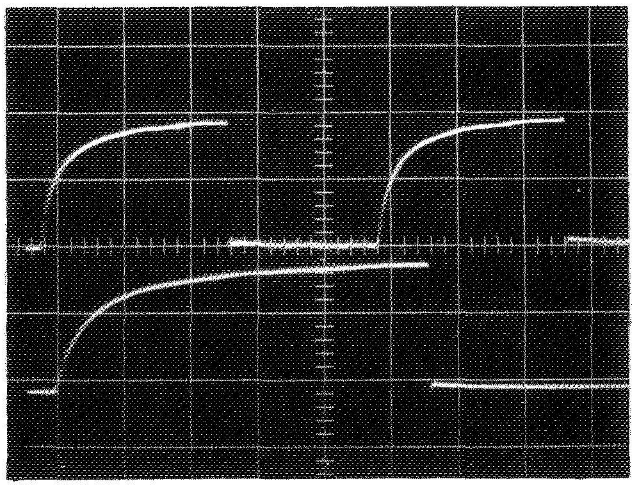
For a 1-Ω unit tested, the current employed was 0.64 A (7 V), and the resistance increase was 1.96% (R_1 = 46,000 Ω; R_2 = 900 Ω), with $\alpha = 100 \times 10^{-6}$ and $\theta_{\max}$ = 200°C. For these conditions, the signal output was 9 mV. Since the cold resistance was 0.92 Ω, the power dissipation I^2R_0 was 0.375 W. A time constant of 6.8 ms was observed, and the calculated γ (= γ') was 1.96 mW/°C, since γ/α was 19.6 W/($\Delta R/R_0$).

IV. Test Results

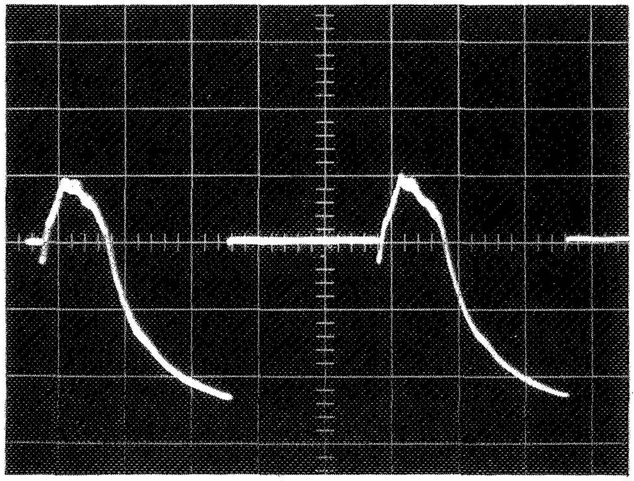
It is apparent that the transient testing technique is applicable as a total inspection tool. In addition to a cold resistance determination, the heat loss factor (thermal conductance) and thermal time constant are obtained. Variations from unit to unit can be explained in terms of process control, and normal and abnormal responses can be ascertained.

Certain abnormal signals raise questions as to meaning and interpretation. For example, instead of a simple exponential rise, a wild variation of signal voltage may appear. Figure 6a shows a normal heating trace at two different sweep rates, whereas Figs. 6b and 6c show abnormal conditions. Figure 7 presents a series of three abnormal traces. It should be noted that most units had normal displays; we can only speculate as to the cause of abnormal displays.

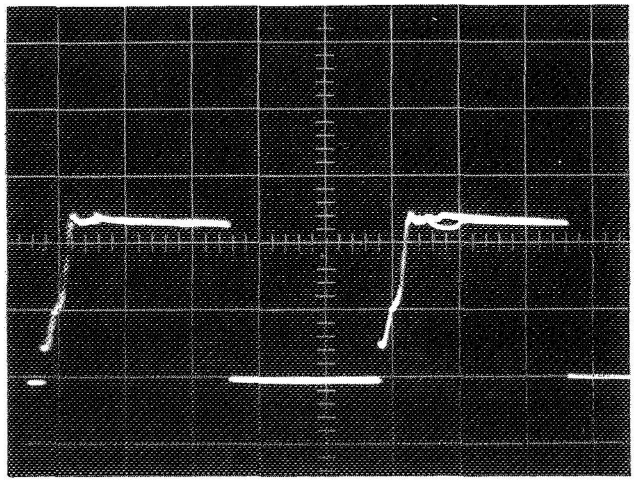
A tabulation of observed data for 1-W/1 A units provided by various manufacturers is presented in Table 1. There is considerable variation among manufactured items depending on the manner in which the 1-W/1 A requirement is obtained (Ref. 5). One could assume that the long time constants are due to heat sinking through the explosive mix wherein heat transmission is a distributed system propagation effect. Time constants of 10 ms are typical with fine bridgewire devices (i.e., 1-mil diameter). If the mass (and heat capacity C_p) is increased together with heat loss γ, it is possible for the time constant ($\tau = C_p/\gamma$) to remain unchanged. The very low time constants are probably a result of efficient heat sinking into the squib header. Unless α is known, the γ/α data cannot be interpreted properly. In Table 1, the low γ/α of sample D1 is probably due to its high α. The unit was tested at the lowest current of 0.3 A and gave large resistance excursions. The wire for F1 was known to have an $\alpha = 100 \times 10^{-6}$ (specifications called for less than 200×10^{-6}), and γ is therefore 2 mW/°C. A 1-W dissipation would result in a 500°C rise for this example.



(a) SWEEP TIME (TOP) = 10 ms/cm, (BOTTOM) = 20 ms/cm
ERROR VOLTAGE = 5 mV/cm



(b) SWEEP TIME = 20 ms/cm
ERROR VOLTAGE = 10 mV/cm



(c) SWEEP TIME = 20 ms/cm
ERROR VOLTAGE = 20 mV/cm

Fig. 6. Test responses: (a) normal; (b) and (c) abnormal

The degree of manufacturing control is also apparent from the data spread. Abnormal traces require different interpretations and should be questioned. The integrity of the wire or thermal interface must be questioned when an abnormal trace is observed, even though the heating process is normal. Certainly the abnormality is a reaction which can be indicative of incipient failure.

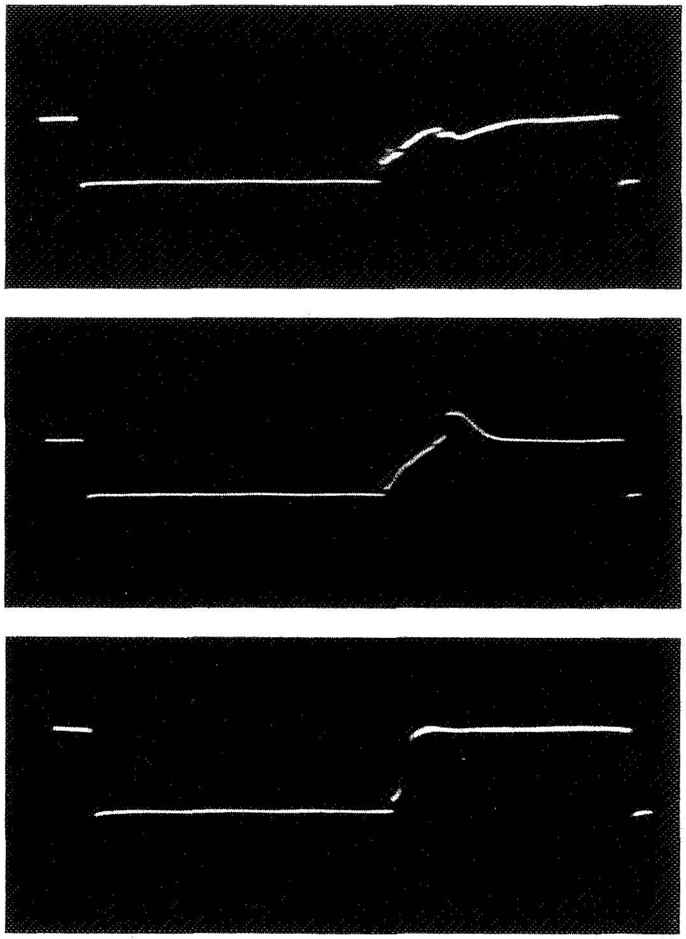


Fig. 7. Test responses: all abnormal

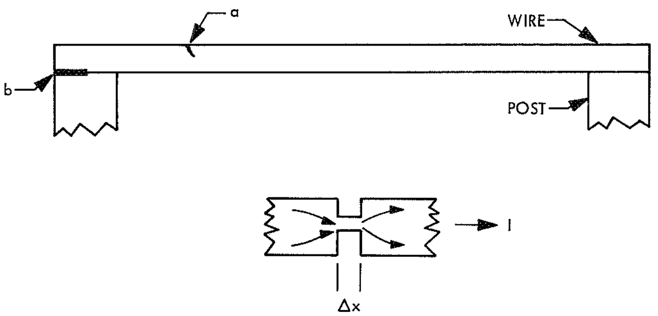
V. Fault and Abnormality Causes

The main purpose of the test procedure described is to detect potential causes of failure. A spread in τ or γ/α is of limited value as long as the thermal responses are normal. By investigating the cause of the fault, the manufacturer may be able to correct a deficiency in his product. For example, a poor bridgewire weld can produce certain nonohmic nonlinearities that will produce a variable voltage drop with constant current. Those nonlinearities that occur at $t = 0$, the onset of the pulse of current, are voltage-sensitive and are due to semiconducting products such as oxides at the interface. Those that occur a small time after the application of power are thermally induced nonlinearities. For example, current flow through a higher resistance gap can cause heating which mechanically or electrically changes the gap. Current crowding (Refs. 6–8), a mechanism responsible for a wide variety of contact nonlinearities, is due to a wire imperfection which results in higher heating. Figure 8a shows a wire radial crack due to a high concentration of current in the Δx section which could cause local heating. The total wire resistance is only slightly increased since the necked-down section introduces an increase in resistance of $R\Delta x$, which is proportional to Δx, the length of the fault. The same phenomenon can occur at the weld section shown at b. Various combinations of this essentially thermal phenomenon are possible.

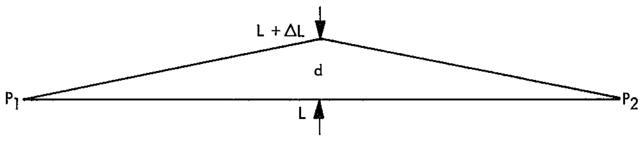
Table 1. Nominal values obtained on 1-W/1-A no-fire devices

Manufacturer's code	Sample size	R_0, Ω	τ, 10^{-3} s	γ/α, W/($\Delta R/R$)	Remarks
A1	8	1.03	3.5	110	One irregular unit
B1	8	1.60	9.0	33	All normal units, small spread
A2	16	1.05	4.5	120	Three abnormal units
C1	12	1.15	8.0	45	All normal units
D1	12	1.03	6.0	6	All normal units, small spread
C2	12	0.6	25[a]	29	Heat curve has long time constant
E1	10	0.94	25[a]	110	Same as C2
A3	24	1.10	9	65	Many abnormal displays (50%)
F1	—	1.00	7	20	A selected group of rejects

[a] From slope data; beyond range of instrument.



(a) CURRENT CROWDING



(b) THERMOMECHANICAL EXPANSION

Fig. 8. Possible causes of abnormal displays

Another thermomechanical effect is due to the coefficient of expansion of the wire[2]. Nichrome V (80 Ni–20 Cr) has a temperature coefficient of expansion of 13×10^{-6}/°C. For a 100-mil-long wire heated to 100°C, $\Delta L = 0.13$ mils. This ΔL can result in a magnified lateral movement of the wire d, as shown in Fig. 8b. If the buckling is approximately triangular, a calculation shows that $d = (\Delta L \cdot L)^{1/2} = (13)^{1/2} = 3.6$ mils. There has been a distance magnification of 28 times. If the posts are rigid, there is movement with respect to the explosive, and this can upset the thermal contact. If the wire confinement due to the explosive dominates, then strains will develop in the wire and possibly in the weld joint. This is a thermal- and time-dependent phenomenon. In repeated testing, secondary fatigue effects may appear and cause failure. Although it would appear that the test has induced this problem, ordinary thermal cycling can result in similar effects. The expansion of the wire generates a "tug" or "pull" on the wire, and the system integrity is checked. The fact that this abnormality only appears in certain cases is indicative of the sensing of a faulty or questionable system.

It is also possible that asymmetrical heating of the weld joints due to differences in resistance has resulted in a thermocouple junction at one post which has not been cancelled out at the other post. Heating a post externally (or internally prior to assembly) would establish a thermal emf level. Other possible causes for the abnormality might be discovered if a fault investigation study was pursued.

VI. Conclusion

The nondestructive testing technique can be used as an inspection procedure in manufacturing and quality control. By balancing the transient bridge, we can obtain important thermal parameters in addition to the nominal resistance. Testing can be performed in a time domain comparable to the functioning times with constant current firing. Capacitor discharge firing would relate more closely to C_p, whereas current firing relates to γ. The described testing technique can provide both types of information.

The test could also be employed to follow the manufacturing process and locate potential weaknesses or lack of control. For example, tests on the bare bridgewire, when compared to those of the loaded unit, are indicative of the degree of thermal coupling. If transient balancing was considered too involved for a quality control operation, only the initial balance need be used, and the signature or display that appeared as an exponential curve could be interpreted directly without any calculations or interpretations.

There are wire–explosive interface irregularities that do not interfere with unit function. Also, there are progressive abnormalities that degrade with time and ultimately result in total failure. Some of the abnormal cases discovered can be exposed to accelerated aging conditions to assess unit stability.

A long-range goal of the study of the mechanisms and causes of failure is the production of a more reliable unit. Short-range goals are to eliminate questionable electroexplosive devices and to reduce the destructive testing aspect of the qualification approval procedure.

---

[2] Suggested by Lloyd Swanson, JPL, Pasadena, Calif.

References

1. Rosenthal, L. A., "Thermal Response of Bridgewires Used in Electroexplosive Devices," *Rev. Sci. Instr.*, Vol. 32, pp. 1033–1036, Sept. 1961.
2. Rosenthal, L. A., "Electrothermal Measurements of Bridgewires Used in Electroexplosive Devices," *IEEE Trans. Instr. Meas.*, Vol. IM-12, No. 1, pp. 17–21, June 1963.
3. Rosenthal, L. A., "Millisecond Switch for Electroexplosive Testing," *IEEE Trans. Instr. Meas.*, Vol. IM-18, No. 1, pp. 19–22, Mar. 1969.
4. Rosenthal, L. A., *Electro-Thermal Equations for Electroexplosive Devices*, NAVORD Report 6684. U.S. Naval Ordnance Laboratory, Silver Spring, Md., Aug. 15, 1959. AD 230917.
5. Menichelli, V. J., *Investigation of Insensitive Electric Initiators*, NOLTR 65-103. U.S. Naval Ordnance Laboratory, Silver Spring, Md., July 6, 1965.
6. Whitley, J. H., "Measuring Contact Construction Resistance," *Electron. Instr. Dig.*, pp. 7–12, July 1967.
7. *Proceedings of the Engineering Seminar on Electric Contact Phenomena.* Illinois Institute of Technology, Chicago, Ill., 1967.
8. Holm, R., *Electric Contacts*, Hugo Gebers Forlag, Stockholm, Sweden.

NASA — JPL — Coml., L.A., Calif.