CONF-800640--17

LA-UR -80-2078

TITLE: ELECTROMECHANICAL SHOCK IN PULSE POWER COMPONENTS

MASTER

AUTHOR(S): T. R. Burkes and W. J. Sarjeant

SUBMITTED TO: Fourteenth Pulse-Power Modulator Symposium
Orlando, Florida
June 3-5, 1980

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

Form No. 836
St. No. 2629
1/75

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

ELECTROMECHANICAL SHOCK IN PULSE POWER COMPONENTS

BY

T. R. Burkes
Electrical Engineering Dept.
P. O. Box 4439
Texas Tech University
Lubbock, Texas 79409

and

W. J. Sarjeant
M. S. 429
Dir. E-4
LASL
Los Alamos, NM 87545

Summary

Most components used in high power pulse generators undergo mechanical shock stresses during the pulse or on its leading edge. As power densities become very high, this shock may lead to anomalous behavior as well as introduce failure modes that may not be immediately obvious. It has been shown that acoustic shock waves traveling within spark gap electrodes can affect electrode erosion by as much as an order of magnitude. Thus, a new point of view is required for component design where shock may be a critical factor. The mechanisms for generation of shock forces, both thermal and electromagnetic, are reviewed and applied to resistors, capacitors, magnetic devices and switches. The mechanisms described are square law effects so that it can be concluded that for high energy pulses, mechanical shock stress will be a critical factor in component survival.

Introduction

In a broad and general way, the mechanisms for the generation of mechanical forces in pulse power components can be ascribed to two mechanisms, thermal shock and forces generated through electrostatic and electromagnetic mechanisms. These forces usually manifest themselves by audible noise generated during the operation of a high power pulse generator. Obviously, something must be moving for the sound to occur and this movement can lead to material fatigue, insulation failure, etc. Also, erratic behavior may be generated by the shock through excitation of mechanical resonances peculer to a particular component. For instance, jitter in an ignitron may be a function of pulse repetition rate because of ripples produced on the mercury surface due to the high magnetic pressure at the arc spot(s).

Under the transmission of microsecond and shorter pulses of electrical energy through power-conditioning components, very rapid deposition of thermal energies into dielectrics and mechanical connections can cause intense localized heating. Depending upon the thermal damage levels of each material, such heating may cause single-pulse catastrophic damage or multiple-pulse accumulative damage resulting in early failure of the component in the system. In the context of the present discussion, the discharge times of interest ($\leq 10^{-6}$ sec.) apply to numerous laser systems and other pulsed systems of current interest. As the thermal diffusion times for even thin films and very good heat sinks are many microseconds [1], the heating in most components will be nearly adiabatic. This discussion will be qualitative in nature and relate these transient thermal and electromechanical effects in capacitors, resistors, and switches to each other.

Thermal Effects

The primary effect of a fast electrical pulse is to cause a sharp temperature increase in dielectrics (e.g., capacitors) or conductive metal surfaces (e.g., thyratrons and spark gaps). Permanent changes are caused by molecular restructuring of the insulators or by sputter damage to metal surfaces. For fast electrical pulses the thermal analysis presented is of general applicability.

In the study of temperature rises at insulator-to-insulator or conductor-to-gas discharge interfaces, a one-dimensional model is generally appropriate [1] as illustrated in Fig. 1. The Region III to left of Region I has the same properties as Region II in most capacitor winding geometries. For switch thermal transfer cases, Region III is normally a glow discharge or arc with a thermal diffusivity much smaller than D_1, meaning that thermal transport back into this region may be neglected. Radiation effects from the metallic collector of Region I are not considered. For this microsecond type time scale, the radial thermal diffusion per pulse is negligible, allowing the three-dimensional heat conduction equation to be simplified from

$$\frac{\partial T}{\partial t} = D\nabla^2 T + \frac{D}{K} U_0. \tag{1}$$

to:

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial x^2} + \frac{D}{K} U_0 \tag{2}$$

where T is the temperature in K, t is time in seconds, x is distance in meters, and U is power density in watts per cubic meter. The constant D is the diffusivity in square meter per second and K is the thermal conductivity of the material in watts per second meter-kelvin. Assuming continuity and negligible temperature rise for very large x, then this equation can be solved as there is no radial or azimuthal temperature variation [2]. Starting from an initial temperature of T_0, if $D_{II} = 0$ then an adiabatic temperature rise takes place in Region I so that

$$T - T_0 = \frac{D_1}{K_1} U_0 t. \tag{3}$$

Thus, this is the maximum temperature rise that can take place and yields a true upper limit, e.g., particularly when thermal diffusion out of Region I takes place slowly.

A second solution to the transient temperature rise is found in the case of depositing thermal energy in Region I, with $D_{III} = 0$ and $D_{II} \to \infty$. The solution has been obtained by Domingos [2] in his excellent study of transient effects in resistors and is of general applicability to capacitor and switch heating. Figure 2 plots the realtionship between temperature rise for a finite layer for different boundary conditions.

The temperature distribution at several times can be obtained for several pulse lengths. For very short times the rise is significant only in the insulator with the peak temperature as given by Eq. (3). Gradually, the thermal energy diffuses into Regions II and III. For most configurations, $D_{II} = D_{III}$ is of interest and the character of the distributions for several times (1-4) is plotted in Fig. 3. Note that cessation of the electrical pulse, after say 1 μs for dielectrics of thickness of a few mils, results in cooling of the insulator by diffusion into the outer regions with a time constant 1/0. This thermal energy gradually diffuses into the substrate environment, such as the metallic (generally aluminous) conductors in a film capacitor or the electrode cooling structure in repetitive switches.

Let us now turn to some examples of transient thermal effects and also some damage situations separate from adiabatic heating wherein the inpulse damage has a dominant voltage effect. Temperature distributions in a one-dimensional model of a film resistor have been calculated by Domingos using a finite difference technique. Assuming an initial equilibrium temperature of T_0, a constant power pulse applied for several pulse durations, the temperature as a function of time is similar to the distribution in Fig. 2. The wings of the distributions illustrate diffusion of thermal energy on a time frame equal to the pulse duration and clearly illustrates the large film temperature rise obtainable for even modest input energies. For example, carbon-film and metal-film resistors suffer damage for input energies from 12 to 200 mJ for 1-μs pulse duration [2]. This is to be compared to 2.4 J for carbon composition resistors where the thermal heating is of a bulk nature in contrast to the film, wherein the vaporization or melting point temperature is readily achieved at much lower energies. As the pulse duration increases it has been observed that the energy threshold for damage rises significantly (10^{-8} J at 10^{-7} s to 10^{-3} J at 10^{-3} s for Allen Bradley carbon-composition resistors) [3]. This may be caused by internal voltage stress-induced breakdown at the higher voltages used at shorter pulse widths [4]. Indeed, the question of accumulated damage with number of pulses has been addressed at some length in the design of high-voltage coaxial attenuators [5]. Previous studies of damage were concerned primarily with large, irreversible (~5-10%) changes in resistance in one single pulse. For electromagnetic-pulse applications this is very useful information for system design. In the development of repetitive pulse systems, it is of more value to assess the accumulative damage with shots and applied voltage. Figure 3 illustrates the per cent resistance change in a 56-Ω, 2-W Allen Bradley carbon-composition resistor as a function of number of pulses, for a lot size of 10 resistors at each voltage level [5]. The pulse width in all cases was 260-ns FWHM. The points are the average for 10 resistors, each resistor being subjected to 1, 10, 100, and 1000 pulses and measured thereafter. The error bars represent the maximum excursions from this average value observed. The dependence of the % R/R upon number of pulses, N, is obtained from a least-squares fit to the data and if V is the peak pulse voltage in kilovolts

$$\frac{\%R}{R} = \frac{V}{5.0} - 0.27 \ln N. \qquad (4)$$

It is presumed that the small, accumulative damage per pulse is caused primarily by superheating at carbon carbon granule interfaces as has been observed by Harton in crystalline, thick-film resistive structures [4]. This gradual reductinn in resistance is of concern in voltage dividers as well as rf circuitry and has prompted a shift to metal film resistors in low-level systems. At higher voltages and powers the problem is considerably more acute, and new structures are required.

Electromagnetic Forces

For most cases, the simplified approach of the description of the force generation mechanisms, i.e. electrostatic and electromagnetic, is justified because of symmetry and the dimensions of components is usually small compared to a wavelength of the excitation current or voltage. In general, the total force generated by an electric or magnetic field can be expressed as

$$f = -\frac{\partial W_f}{\partial x} \left| \begin{array}{l} q = \text{const. (capacitors)} \\ \phi = \text{const. (inductors)} \end{array} \right.$$

where W_f is the total energy stored in the filed, x is a dimension and q is the charge on conductors (for electrostatic fields) and ϕ is the magnetic flux (for electromagnetic fields) [6]. In general, forces derived from electromagnetic fields act to change the circuit or component dimensions to increase the total energy stored. For magnetic fields, it can be further said that the magnetically derived forces will act to reduce localized energy density, even though overall energy storage will increase. Electric fields, on the other hand will produce forces that act to increase energy density.

Electrostatic Forces

The force exertod on the dielectric in a capacitor may be expressed as

$$f = \frac{1}{2} V^2 \frac{dC}{dx}$$

where V is the applied voltage, x is a dimension and C is the capacitance expressed as a function of x. Thus, if C is given by

$$C = \frac{\epsilon A}{x}$$

where ϵ is the permitivity, A is the area of the capacitor plates and x is the plate separation. The compressive force exerted on the dielectric is

$$f = -\frac{1}{2} V^2 \frac{\epsilon A}{x^2}.$$

This formulation gives a pressure of about .1 lb/in^2 for an electric field stress of 6 Mvolts/meter in mylar. This mechanical force is exerted by the capacitor plates on the dielectric so that a squeezing action is transmitted to the oil (impreginate) and a pumping action is initiated. Thus, the capacitor vibrates at the pulse repetition frequency. Because of the usual construction of capacitors, this force will be most predominant on the outermost layer. The internal forces will be largely countorbalanced except at localized points such as foil wrinkles.

If the highest dielectric material in a capacitor does not fill the complete volume between the capacitor plates, then a stretching force is exerted on the higher dielectric material in directions to fill the capacitor. This effect can be seen by expressing C as $C = \frac{\epsilon l x}{d}$.

where d is the plate separation, l is the plate length and x is the dimensional direction in which the dielectric does not fill the area between the plates. Thus, the stretching force is given by

$$f = \frac{1}{2} V^2 \frac{\varepsilon l}{d}.$$

From this formulation it can be seen that the higher dielectric materials are attracted to the highest field regions (the foil edges). Further, any high dielectric impurities will be attracted to the high field regions. It also follows that the low dielectric materials will tend to be displaced by the high dielectric materials. If low dielectric materials are suspended in a high dielectric fluid where a significant electric field gradient is present, a churning action may be observed.

Magnetic Forces

Since magnetic fields and thus inductances are inherent in any electrical circuit, a useful formulation for the magnetic forces is given by

$$f = \frac{1}{2} i^2 \frac{dL}{dx}$$

where i is the current and L is the inductance expressed as a function of x. This formulation ignores the nonlinearities of iron. It is none-the-less useful for visualization of the character of magnetically derived forces of electrical circuit components.

Inductance may be expressed functionally as

$$L = f\left(\frac{N^2 \mu A}{l}\right)$$

where
N = turns,
μ = permeability,
l = magnetic path length,
A = cross sectional area of magnetic path.

clearly, the forces on a current loop are such that the magnetic length tends to shorten and the cross sectional tends to increase. Thus an inductor undergoes an axial compression as well as expansive force. In the event that iron is present, the iron undergoes a compressive force along the magnetic path (magnetostriction) and a very noticeable "thump" is associated with iron core devices used in pulse power systems. This mechanical motion generates losses in pulse transformers, charging inductors, etc. not accounted for by eddy current and hysterysis losses since mechanical work is being done which is not returned to the electrical circuit.

Magnetic fields may become especially intense at circuit configurations such as angle turns or U-shaped bends. Situations involving turns may be depicted by the arc channel and the electrodes of spark gaps. This configuration can exert sufficient force on the electrode to generate acoustic waves into the electrode [7]. Thyratron anode cups represent a case of a U-shaped revolution. At very high di/dt operation, the current will run along the anode skin and conisderable force may be exerted on the walls and bottom of the anode cup.

Situations involving concentration of magnetic fields may be more appropriately described by

$$f = \frac{\partial}{\partial x}\left[\int_v \tfrac{1}{2}\mu H^2 dv\right]$$

where v is the volume of interest. Manipulation of this equation results in a magnetic pressure [8]

$$p = \tfrac{1}{2}\mu H^2.$$

This pressure may be exerted directly on the surface of conductors causing a considerable shock wave to be developed. (The exact nature of the pressure pulse depends on the circuit configuration and the reader is referred to ref. 8.) Those situations involving geometries where magnetic fields are concentrated can be expected to undergo considerable mechanical stress during the discharge.

Conclusions

Because most materials expand when heated, transient adiabatic heating of pulse power components can lead to extreme internal stresses in pulse power components. When these stresses are combined with those due to electromagnetic forces, especially magnetic effects, various failure mechanisms become clear. A resistive conductor undergoing a rapidly rising, high current pulse may develop surface cracks and pitting due to the sudden shock forces exerted on its outer layer ($<$ one skin depth). The thermal stress in SCRs may be especially severe under pulse loading [9]. Because considerable energy will be deposited in the depletion region upon turn on, this region will expand sufficiently to vibrate the crystal. Repetitive pulsing may then lead to mechanical fatigue.

Electromagnetic and thermal forces may produce sufficient shock for high di/dt operation to over stress insulator/conductor interfaces so that leaks occur. Simple metal-to-metal contacts which are not uniform are forced apart by the uneven current distribution. Thus, pitting and arcing may occur within metal connection so that performance suffers as well as early failure.

Although electrostatic forces are usually weak, they none-the-less can lead to troublesome problems. High dielectric impurities are attracted to the points of highest field stress. For instance, oxides of aluminum do not have high breakdown strength but would be attracted to the highest fields leading to corona and/or breakdown.

As energy densities increase, the consequences of mechanical motion and shock can be expected to introduce early failure modes and anomalous behavior. It should be noted that the mechanisms for the production of shock stresses are square law effects. The application of transient thermal diagnostics to other electrical energy storage and transfer components will become a matter of more concern in the future as repetitive high-average power applications continue to expand. This, along with electromechanical effects, may well turn out to represent a limit to present system scalability and point toward the research and advanced development activities, which will then be required to meet future applications.

References

1. H. Domingos, "Transient Temperature Rise in Film Resistors," Rome Air Development Center Technical Report RADC TR-74-92, April 1974.

2. H. Domingos, "Electro-Thermal Overstress Failure in Microelectronics," Rome Air Development Center Technical Report RACD-TR73-87, April 1973.

3. H. Domingos, "Pulse Power Effects in Discrete Resistors," to be published as a DNA report.

4. J. P. Marton, private communication.

5. W. J. Sarjeant, "A 50-ohm Coaxial High-Voltage Attenuator with 80 Pico-second Rise Time," unpublished.

6. S. Seely, Electromechanical Energy Conversion, McGraw-Hill, 1962.

7. R. Petr and T. R. Burkes, "Acoustic Phenomena In Erosion of Spark Gap Electrodes," Applied Physics Letters, Vol. 36, April, 80.

8. H. Knoepfel, Pulsed High Magnetic Fields, North-Holland Publishing Co., 1970.

9. G. Karady and R. Cassel, "Design Philosophy of 600 MN Pulsed Energy Converters for Toroidal Field Coil of TFTR at Princeton," Proceedings of the Seventh Symp. on Engr. Problems of Fusion Research, Vol. I, Oct. 25, 1977.

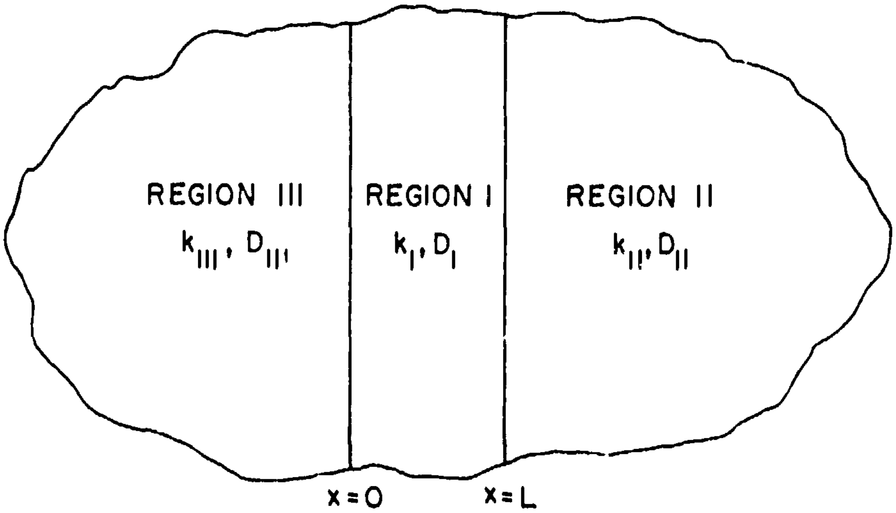

Fig. 1. One-dimensional model of a film resistor. Region I is the resistive film, Region II is the substrate, and Region III is the insulating jacket (Ref. 2)

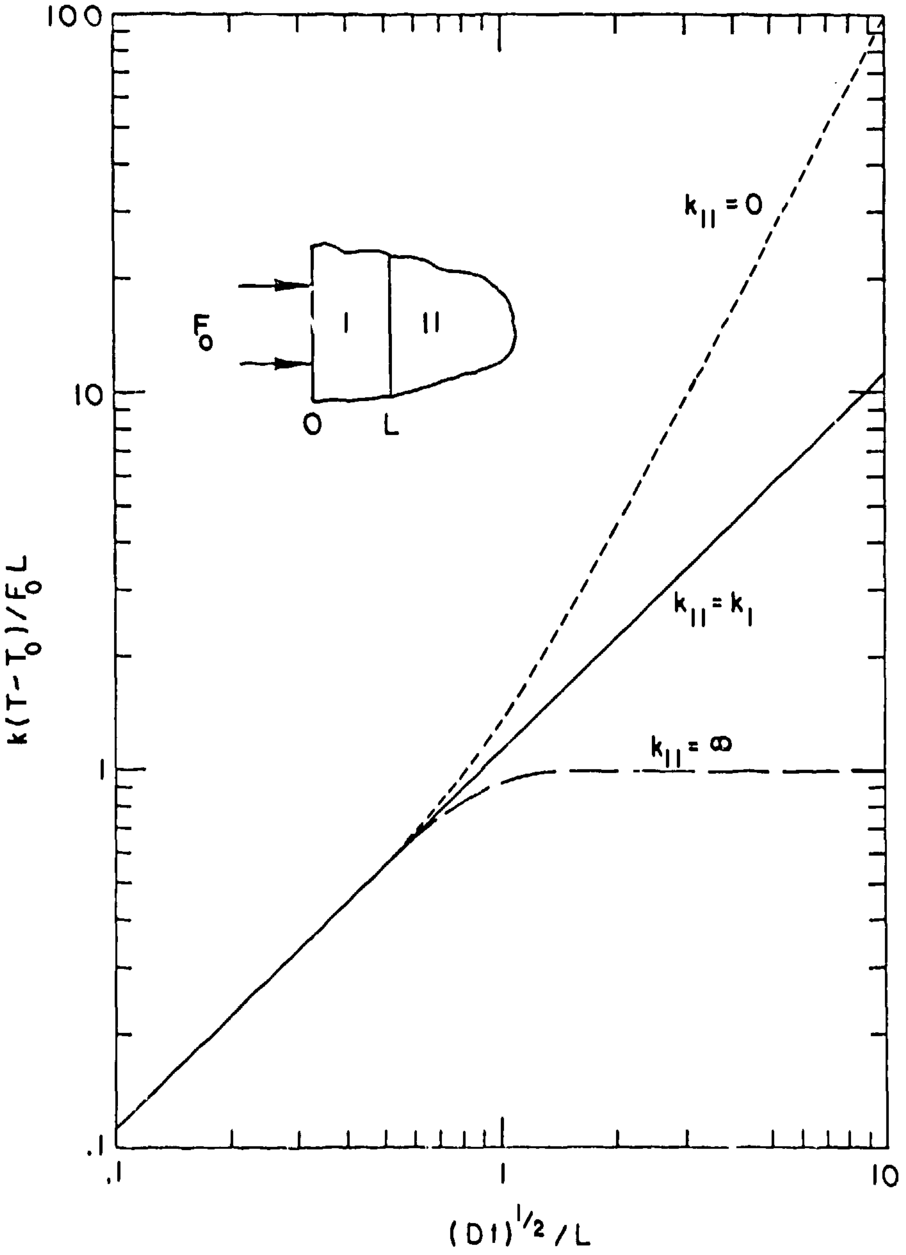

Fig. 2. Peak temperature rise in a finite layer with different boundary conditions. Region II is a perfect insulator in the top curve, a perfect heat sink in the bottom curve, and has the same thermal properties as Region I in the center curve. (Ref. 2)

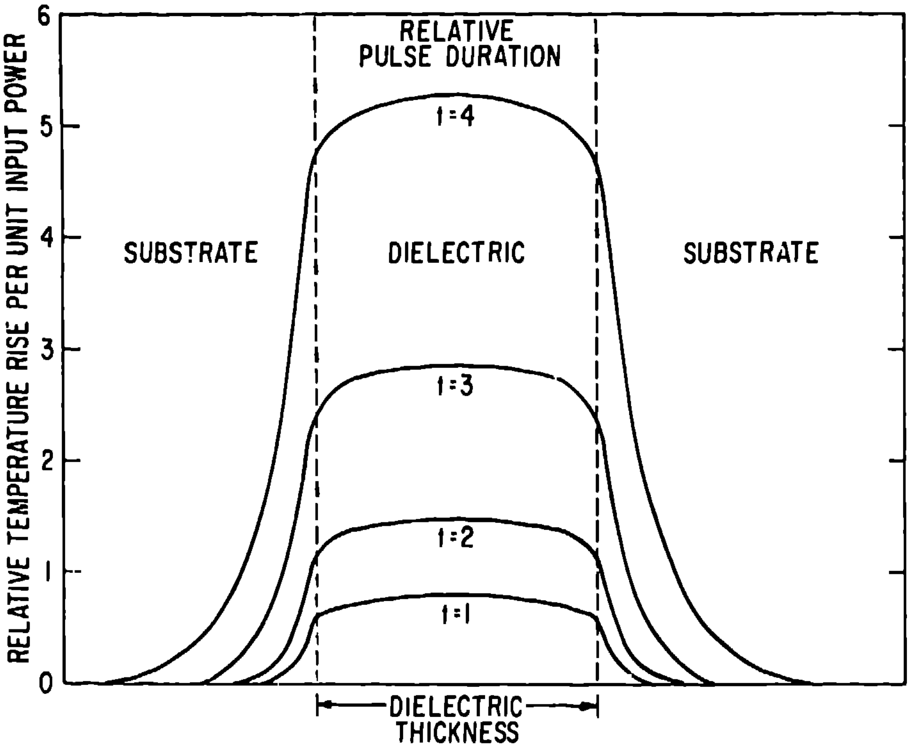

Fig. 3. Illustration of the transient temperature rise per unit input power in a dielectric film surrounded on either side by a thermally high diffusivity substrate. As the pulse duration increases, the thermal effects change from adiabatic heating to significant heat flow during the pulse.

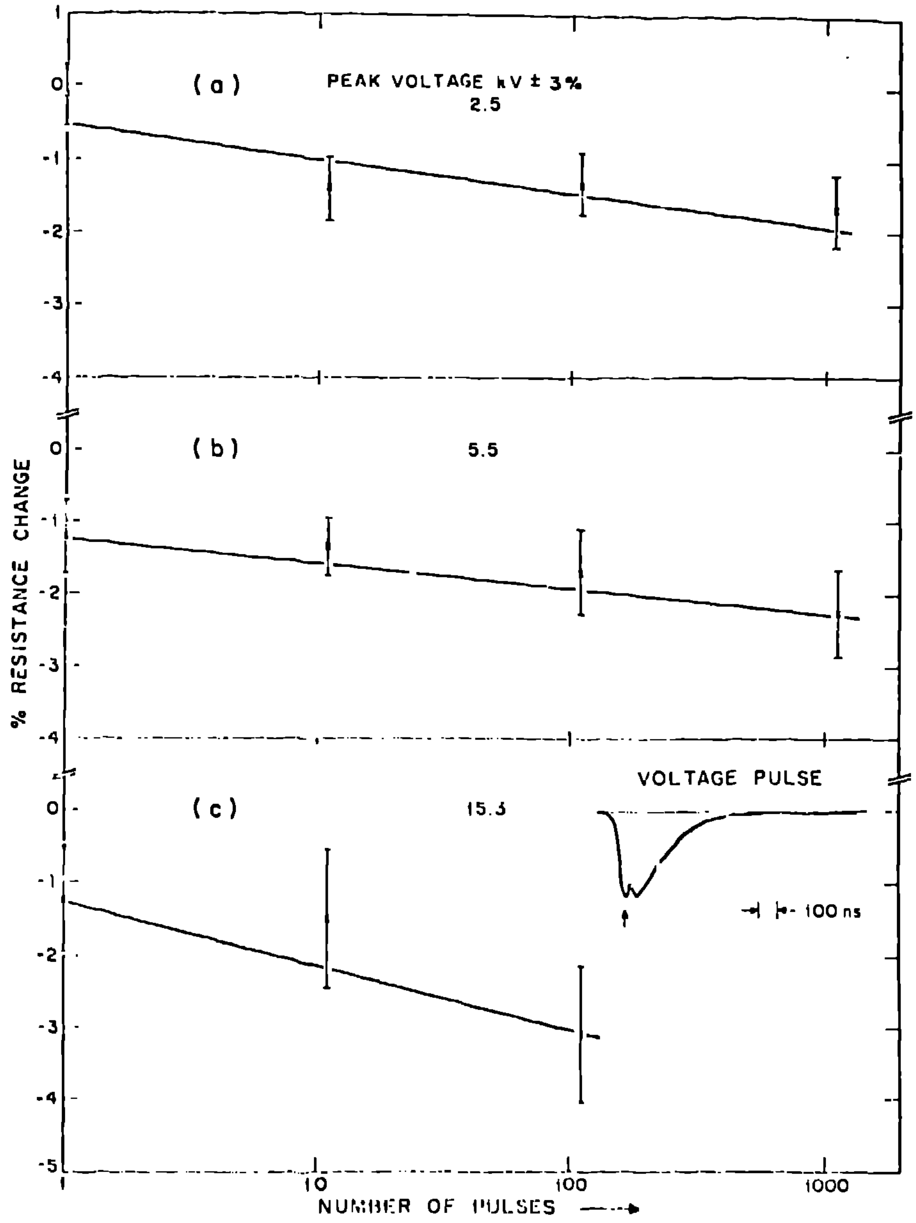

Fig. 4. The per cent resistance change in 56-Ω, 2-W Allen Bradley carbon-composition resistor as a function of number of pulses, for a lot size of 10 resistors at each voltage level.