

# A COMPARATIVE EXPERIMENTAL STUDY OF CAPACITOR DIELECTRICS UNDER RINGING CONDITIONS

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## Abstract

Five different types of pulse power capacitors, each with a different dielectric material, were evaluated in an underdamped circuit. The purpose of these measurements was to determine the applicability of the various capacitor technologies for use in circuits where severe ringing will be required. Such circuits could include induction type electromagnetic launchers. It was found that severe losses, due to the effective series resistance (ESR) of the capacitors, manifested themselves. This places severe restrictions on the application of such components to circuits that require highly efficient transfer of energy from energy storage to the load. The degree of the loss varies considerably from capacitor dielectric to dielectric and from electrode construction to electrode construction.

## Introduction

The U.S. Army Pulse Power Center at Fort Monmouth, NJ, has been performing component evaluation on behalf of Polytechnic University, NY, for a research program that they are conducting on inductive type electromagnetic launchers. The work is being sponsored by the Army's Space and Strategic Defense Command. The launcher is termed the Linear Induction Launcher (LIL) and has been reported on in prior literature [1-2]. This system, in brief, generates, by means of ringing RLC circuits, a series of damped sine waves at different points along the launcher. A tubular armature receives energy, inductively, and "rides the wave" down the launcher. As it moves down the launcher, it acquires desired launch velocity.

The need to apply energy and accelerate the armature necessitates the efficient coupling of energy from energy storage capacitors to the armature. First experiments focused on the application of the accelerating pulses to the launcher and to the armature at the proper time intervals. In other words, this was at first a switch problem, with concern for the amount of losses incumbent in the switches, which would more than likely be ignitrons and spark gaps, given the voltages and duty these switches would most likely see.

However, it soon became apparent that the more critical factor was the equivalent series resistance (ESR) of the energy storage capacitors. Higher than expected values of ESR caused us

to devise new ways of extracting energy efficiently from the energy storage elements. The Pulse Power Center has, over the years, amassed a considerable collection of various types of energy storage capacitors, with various types of dielectrics and electrode constructions. It was determined that, before we would go on with further tests for the inductive launcher components, we perform a side by side comparison of various types of capacitors under the underdamped, ringing conditions that would be necessary for the proper operation of the launcher.

## Experimental Devices and Apparatus

The capacitors tested have their construction and properties listed in Table 1. The test apparatus is shown schematically Figure 1 and photographically in Figure 2.

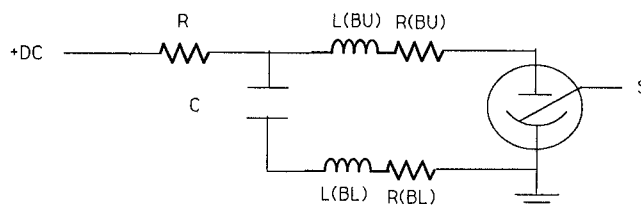


Figure 1. Schematic of capacitor test apparatus, where L(BU) and L(BL) are upper and lower buswork inductance, respectively, and R(BU) and R(BL) are upper and lower buswork resistance, respectively. R is a charging resistor.

Testing was quite straightforward. A capacitor under test was charged to 500 V and then discharged into a short circuit through a switch. The switch was a Richardson NL 8900 ignitron, similar to switches envisioned for the launcher. The only inductance and resistance in the circuit are due to the buswork.

The results of the ring down test are shown in Figures 3-13. In all but two cases, identical capacitors are operated in series or parallel, in order to simplify measurements. Determining the frequency of the waveform and knowing the capacitance allows the dissipation resistance (RESR) to be calculated by the equation:

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1. REPORT DATE <b>JUN 1993</b>	2. REPORT TYPE <b>N/A</b>	3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>A Comparative Experimental Stijdy Of Capacitor Dieleclrics Under Ringing Conditions</b>		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Army Research Laboratory Pulse Power Components Branch ATTN: AMSRL-EP-MC Fort Monmouth, NJ 07703-5601</b>		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>			
13. SUPPLEMENTARY NOTES <b>See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.</b>			
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15. SUBJECT TERMS			
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	<b>SAR</b>
			18. NUMBER OF PAGES <b>4</b>
			19a. NAME OF RESPONSIBLE PERSON

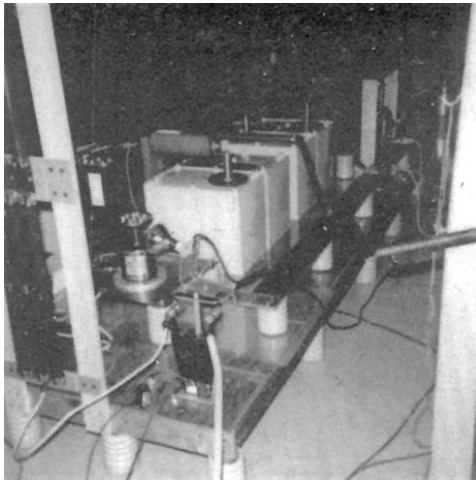


Figure 2. Photograph of capacitor test apparatus with sample capacitors installed. Ignitron switch is at left.

TABLE 1  
Characteristics of Capacitors Tested

Capacitor	Capacitance	Voltage	Construction
A	0.05 $\mu$ F	15 kV	Paper/Polypropylene/Extended Foil
B	0.05 $\mu$ F	40 kV	Polypropylene/Extended Foil
C	1.9 $\mu$ F	40 kV	Paper/Polyester/Tab Foil
D	0.9 $\mu$ F	40 kV	Paper/Polyester/Tab Foil
E	50 $\mu$ F	44 kV	Paper/Extended Foil
F	175 $\mu$ F	22 kV	Paper/Polyester/Metallized Extended
G	342 $\mu$ F	16 kV	Polypropylene/Metallized Extended
H	900 $\mu$ F	16 kV	Polyvinylidene Fluoride/Metallized Extended

$$RESR = \sqrt{\frac{4L}{C} - 4L^2 \omega^2 - R(B) - R(S)}, \text{ where (1)}$$

$\omega = 2\pi f$   $f$  = frequency of sine wave  
 $L$  = circuit inductance = 1.85  $\mu$ H  
 $C$  = capacitance of device (s) under test  
 $R(B)$  = bus resistance - 2.319 mohms  
 $R(S)$  = switch resistance = 360  $\mu$ ohms

and percent dissipation (%DF) calculated by the equation:

$$\%DF = 100 \omega C RESR \quad (2)$$

Note that equation 2 reflects the frequency dependence of the ESR.

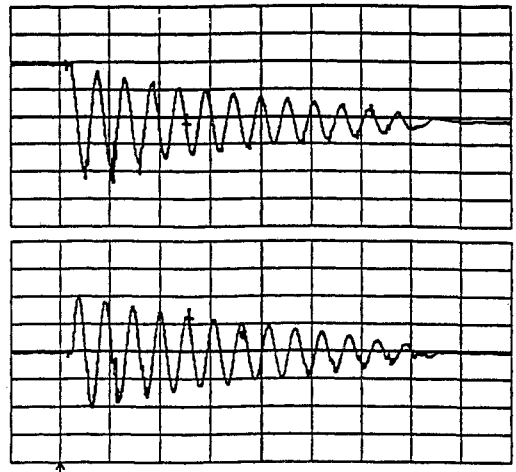


Figure 3. Two type A capacitors in parallel. Upper trace: Voltage 200 V/div. Lower Trace: Current 500 A/div. Horizontal Axis: 5 $\mu$ s/div.

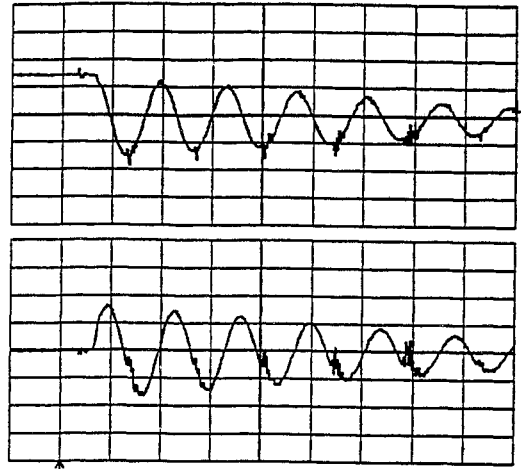


Figure 4 Two type B capacitors in parallel. Upper trace: Voltage 400 V/div. Lower tract: Current 500 A/div. Horizontal Axis: 2  $\mu$ s/div.

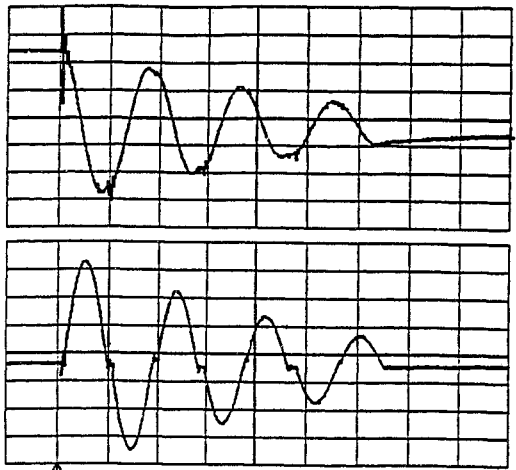


Figure 5. Two type C capacitors in parallel. Upper trace: Voltage 200 V/div. Lower trace: Current 200 A/div. Horizontal axis: 10  $\mu$ s/div.

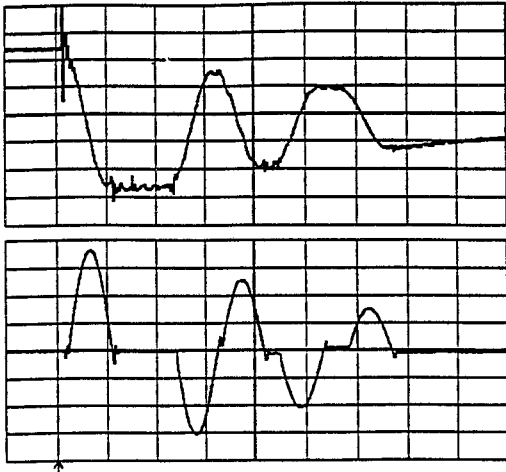


Figure 6 Two type C capacitors in series. Upper trace: Voltage 200 V/div. Lower trace: Current 100 A/div. Horizontal axis: 5  $\mu$ s/div.

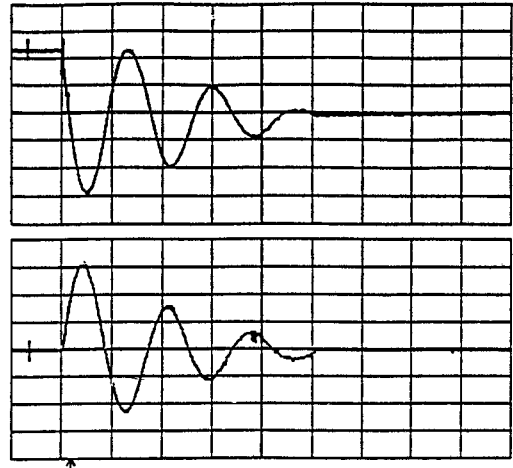


Figure 9. Two type F capacitors in Parallel. Upper trace: Voltage 200 V/div. Lower trace: Current 2000 A/div. Horizontal Axis: 100  $\mu$ s/div.

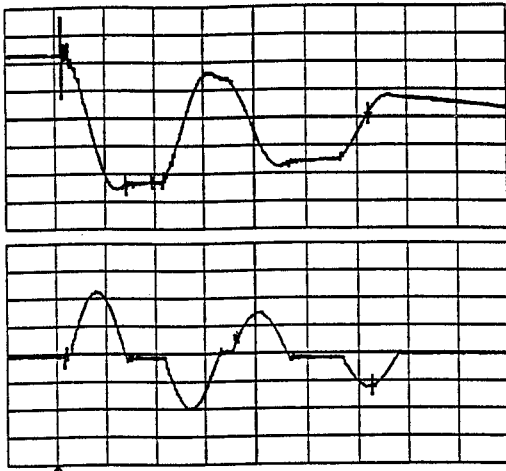


Figure 7. Two type D capacitors in parallel. Upper trace: Voltage 200 V/div. Lower trace: Current 200 A/div. Horizontal Axis: 5  $\mu$ s/div.



Figure 10. Two type F capacitors in series. Upper trace: Voltage 200 V/div. Lower trace: Current 800 A/div. Horizontal axis: 50  $\mu$ s/div.

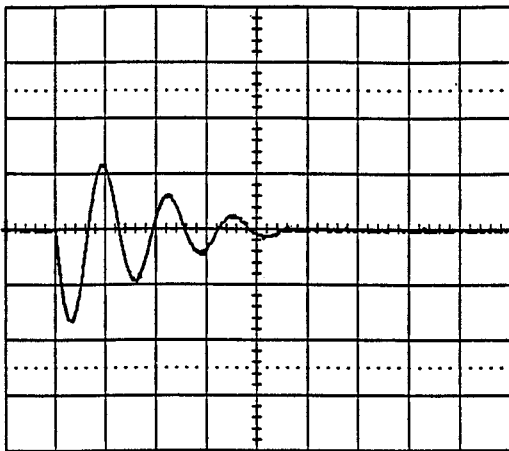


Figure 8. Type E capacitor. Vertical Axis: Current 1000 A/div. Horizontal axis: 50  $\mu$ s/div.

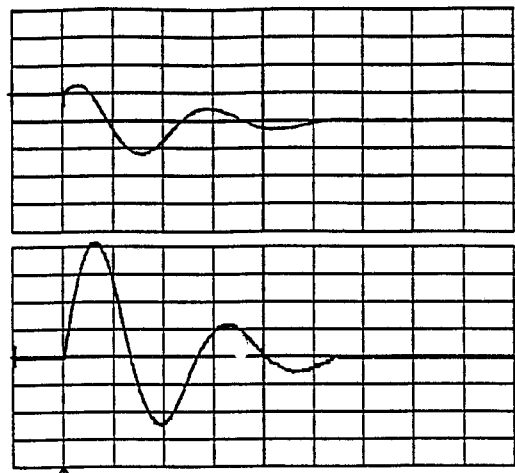


Figure 11. Two type G capacitors in parallel. Upper trace: Voltage 500 V/div. Lower trace: Current 2000 A/div. Horizontal axis: 100  $\mu$ s/div.

TABLE 2

## Summary of Test Results

Capacitor	Data on Figure:	RESR	Frequency	%DF
A	3	284 m $\Omega$	385 kHz	3.4
B	4	312 m $\Omega$	380 kHz	3.7
C	5	141 m $\Omega$	60 kHz	10
C	6	82 m $\Omega$	110 kHz	5
D	7	270 m $\Omega$	90 kHz	14
E	8	35 m $\Omega$	16 kHz	18
F	9	28 m $\Omega$	6 kHz	18
F	10	16 m $\Omega$	11 kHz	10
G	11	46 m $\Omega$	3.7 kHz	37
G	12	40 m $\Omega$	6 kHz	26
H	13	9 m $\Omega$	3 kHz	14

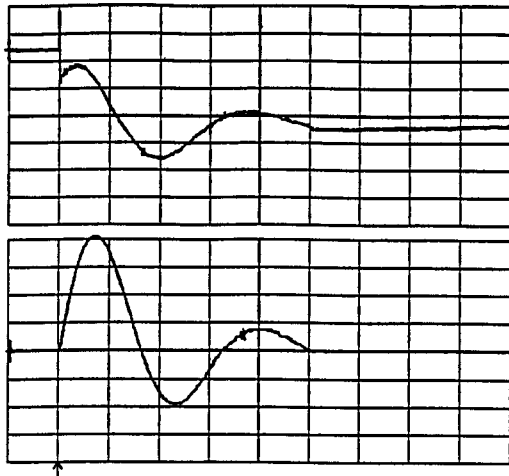


Figure 12. Two type G capacitors in series. Upper trace: Voltage 200 V/div. Lower trace: Current 800 A/div. Horizontal axis: 50  $\mu$ s/div.

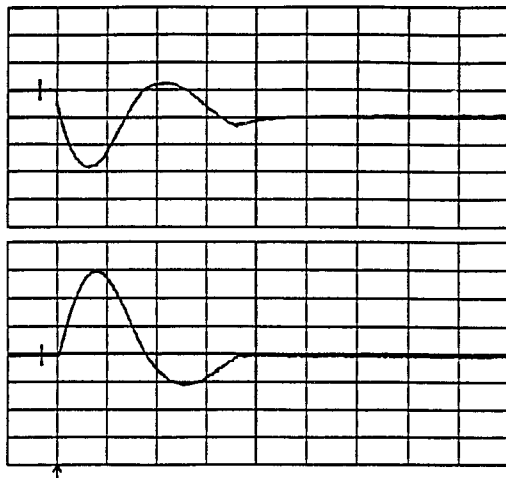


Figure 13. Type H. capacitor. Upper trace: Voltage 500 V/div. Lower Trace: Current 2000 V/div. Horizontal axis: 100  $\mu$ s/div.

The results of the tests are shown in Table 2. It may be seen that the best results, i.e. the lowest percent dissipation, are obtained from paper/polypropylene/extended foil capacitors and polypropylene/extended foil capacitors. This not surprising, in that the low dissipation factor of polypropylene is well known. Of interest is to compare the dissipation factor of polypropylene/extended foil capacitors with polypropylene/metallized extended capacitors, the latter having a dissipation factor an order of magnitude higher. In examining the data in Table 2 by capacitor type, it may be seen that, for the purposes of a ringing discharge requirement, the older designs have an advantage over the newer types.

Also of interest is the comparison between Figures 5 and 6, and 11 and 12. Here, measurements are made for the same capacitor at different frequencies. Note that the dissipation factor decreases at increasing frequency, a phenomenon that is well known but difficult to quantify [3-4]. There may be an advantage to this if the capacitor is used in a latter section of the launcher, where the faster flight time necessitates a higher frequency of the accelerating current.

It should be noted that the capacitors tested had been previously used, so some deterioration due to aging and use had taken place. Also, no effort was made to use a capacitor optimized to application to a particular launcher or stage of a launcher. Nevertheless, we believe these experimental tests are significant in determining the type of capacitor best suited for use in a ringing circuit for an inductive launcher of this type.

### Conclusion

Based on a comparison of experimental data of various types of capacitors in side by side testing, we conclude that capacitors with polypropylene dielectrics and extended foil electrodes are the prime candidates for use in a linear induction launcher modulator circuit, operating under a ringing condition.

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