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SELF-HEALING PULSE CAPACITORS FOR THE NATIONAL IGNITION FACILITY (NIF)

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Abstract

Approximately 4,000 capacitors, each storing 83.5 kJ of energy, will be required for the United States Department of Energy National Ignition Facility (NIF), being built at Lawrence Livermore National Laboratory (LLNL). To achieve the required system reliability, lifetime, and cost goals, the capacitors were specified to be of the self-healing, metallized electrode type of construction. Maxwell Energy Products has previously delivered a number of banks of self-healing capacitors, including the 52 MJ bank at the U.S. Army ARDEC facility at Picatinny Arsenal, NJ. Development of capacitors specifically for NIF began several years ago and continues today at Maxwell, with the primary goal of reducing the manufacturing cost. In support of this effort, LLNL has procured prototypes and life tested a number of our designs over the past three years.

This paper will review the development of NIF capacitors at Maxwell, focussing on the lifetime performance of different designs during the development. This work has resulted in Maxwell Type CM capacitor designs whose demonstrated lifetime capability has far exceeded the 20,000 shot NIF requirement, having energy densities as high as 0.84 J/cc.

I. BACKGROUND

Until about 1986, pulsed power capacitors supplied by Maxwell were almost always built with discrete foil electrodes. At that time, the need for higher energy density energy stores for mobile electromagnetic launchers and directed energy weapons drove the development of self-healing, metallized electrode capacitor designs. The first commercial products of this type, introduced in 1986, were external cardiac defibrillator capacitors, typically storing 450 Joules at rated voltages between 4 and 6 kV. In parallel with this development, Maxwell prototyped and tested 25-50 kJ energy storage capacitors.

A. Defibrillator Capacitors

Defibrillator capacitors represent excellent "scale-model" capacitors for developing energy storage capacitor technology at the basic dielectric-electrode level. Maxwell has supplied over 200,000 self-healing defibrillator capacitors worldwide. These capacitors take advantage of the self-healing capability for increased energy density, reduced cost, and high reliability. Four generations of self-healing defibrillator capacitor technology have been developed over the past 13 years. The third and fourth generation designs correspond to Maxwell's prototype NIF capacitor designs Type A and Type B.

Our experience with thousands of defibrillator capacitors indicates the strengths and weaknesses of these dielectric/electrode designs. Whereas Type A capacitors have not been observed to fail due to internal short-circuits in our life tests, Type B capacitors have been observed to fail internally under life test conditions that allow thermal runaway in localized areas around poor self-healing sites (not under normal heart defibrillator operation). The terminations of Type B capacitors are also much more susceptible to damage from discharges into low impedance faults. Nevertheless, Type B capacitors are desired due to their lower cost and light weight.

B. Energy Storage Capacitors

In 1988, Maxwell supplied prototypes of self-healing energy storage capacitors to Lawrence Livermore National Laboratory (LLNL) for evaluation on the ATHENA program. Models 36043 and 36044 were 103 uF and 206 uF units rated at 20 kV. Maxwell later was qualified, but not selected as the supplier, for the BEAMLET capacitors, 206 uF, 22 kV, 50 kJ.

In 1990-1991, Maxwell built and delivered the 52 MJ bank of 206 uF 24 kV 50 kJ self-healing capacitors at the U.S. Army ARDEC's Electric Armaments Research Center at Picatinny Arsenal, New Jersey [1]. These capacitors were an early version of the Type A technology. Model 32511 was 305 x 457 x 387 mm in size, and had an energy density of 0.93 J/cc. The design life was 5000 shots.

Other relevant developments included self-healing hybrid electrode capacitors such as Maxwell's Model 36216, rated at 210 uF at 15 kV, used in the OMEGA Laser Upgrade at the University of Rochester [2]. This capacitor design approach has also been successful in long-life repetitively pulsed industrial applications, where high reliability is required, such as food packaging sterilization.

Table 1. NIF Capacitor Requirements [3].

Parameter	Unit	value
Capacitance/ Tolerance	**uF/ %**	**290 –0 +10%**
Nominal Operating Voltage	**kV**	**24.0**
Maximum Operating Voltage	**kV**	**26.0**
Nominal Energy	**kJ**	**83.5**
Rated Voltage Reversal	**%**	**10**
Maximum Voltage Reversal (Fault)	**%**	**65**
Rated Peak Current	**kA**	**30**
Maximum Peak Current (Fault)	**kA**	**95**
Operating Temperature	**C**	**+10 to +40**
Minimum Life at 26.0 kV	**Charge/discharge cycles**	**100**
Minimum Life at 24.0 kV	**Charge/discharge cycles**	**20,000**
Minimum Life at Fault Conditions	**Charge/discharge cycles**	**25**
Maximum Discharge ESR	**milliohms**	**25**
Maximum Dimensions	**mm**	**457 x 489 x 960**
Type of Capacitor		**Self-healing**

II. NIF CAPACITOR REQUIREMENTS

The capacitors for the National Ignition Facility are designed to meet or exceed the specifications listed in Table I.

An important aspect of the specification is that the acceptable capacitance range depends on the value of the "Equivalent Series Discharge Resistance" or ESDR. The ESDR is defined to be:

$$ESDR = \left(\tfrac{1}{2} Co\, V_{ch}^2 - \int i_{cap}\, v_{cap}\, dt\right) / \int i_{cap}^2\, dt \quad (1)$$

where Co is the measured capacitance, Vch is the charge voltage (e.g. 24 kV), icap is the discharge current and vcap is the capacitor terminal voltage at time t during the discharge. The first term in the numerator is the ideal delivered energy and the second term is the measured value. The denominator is the measured action (Amp^2–sec or Joules/ohm). Thus, the ESDR is a measure of the energy loss during discharge. The NIF capacitor specification requires that the minimum capacitance value be greater, the greater the value of the ESDR, in order to achieve the required delivered energy [3].

III. DEVELOPMENT METHODOLOGY

The primary driver for the NIF capacitor development effort was cost reduction. This led us to confine our focus to low cost dielectric and electrode materials, and to maximize energy density within that constraint. Another goal was to minimize machine time and labor, which drives the development of designs toward a small number of windings made from the widest possible material webs. The width of the capacitor elements, or "sections", was constrained by both the current carrying capability of the terminations and the required ESDR. Thus, Maxwell's initial designs were based on multi-section windings of 300-635 mm width, in which two or more capacitances are connected in series within each winding. The dielectric materials and layer thicknesses were based on defibrillator and other previous capacitor design experience.

Initially, full-size prototypes of the least risk designs and scale-models of the higher risk designs were built and tested in parallel. Samples of the scale-model capacitors were initially subjected to a Maximum Voltage Test and a Short-Circuit Current Test to establish their maximum voltage and current ratings. The Maximum Voltage Test consisted of a series of 60 second voltage withstand or hipot tests at increasing voltage levels, with capacitance and DF measured after each step. In this test the capacitor was discharged through a high resistance load. The Short-Circuit Current Test involves discharging the sample capacitor through a low impedance circuit 5 times at each voltage level, measuring the peak current and reversal of the pulse, and measuring the capacitance and DF after each stress level. Note that the voltage levels in the Short-Circuit test are typically much lower than in the Maximum Voltage Test. The peak current levels are translated to those for a full-sized 290 uF 24 kV NIF capacitor given the capacitance of the sample and the number of series elements that would be required.

When these initial screening tests indicated that the design met expectations, the remaining samples were acceptance tested and then life tested. Acceptance Testing included capacitance and DF measurements, a hipot test, a pulse discharge test, and a gross leak test. Some samples would then be further characterized by measurements of capacitance and DF over the frequency range from 100 to 10,000 Hz, and insulation resistance. Figure 1 shows the projected ESR for four hypothetical NIF capacitor designs based on such model capacitor data.

Life tests were carried out so as to simulate the NIF operation as closely as possible. This was done by testing the model at the voltage that would be equivalent to 24 kV on the NIF capacitor, adjusting the load so as to obtain

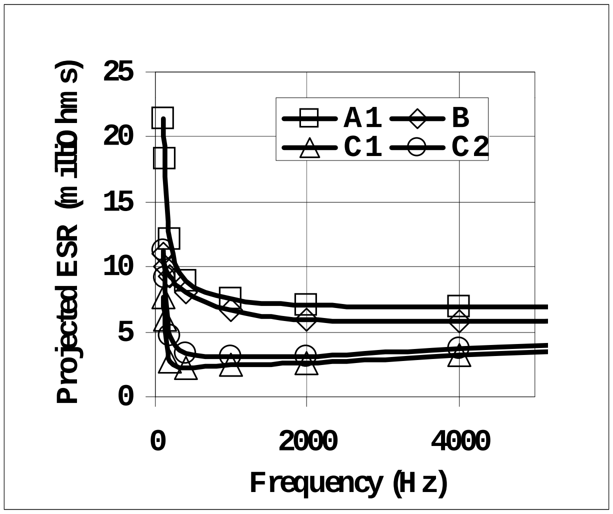

Figure 1. Projected ESR of NIF capacitor designs.

the same current per unit capacitance and voltage reversal as expected in the elements of the full-scale capacitor, and setting the hold time at voltage to 15 seconds. The pulse repetition rate was allowed to be higher than in full-scale life tests, due to the better cooling in small scale models.

Figure 2 shows an example of the life test data obtained for one type of capacitor, designated here as Type C1. During the test, periodic measurements of the capacitance and DF were made, and the case was examined for swelling from internal gas pressure buildup. In this particular case, because the life at 4.0 kV far exceeded the 20,000 shot requirement, an additional life test was run at 4.4 kV to determine if the dielectric film thickness could be reduced by 10% in the next iteration. A dramatic reduction in life was observed, equivalent to a voltage exponent of –24. (The initial increase in capacitance which is observed here is due to electrostriction of relatively loose windings.)

Based on such test results, and accompanying failure analysis of the units, each design approach was either scaled up to a full-size prototype, modified and iterated, or abandoned.

Full-size capacitors were prototyped in small numbers (typically 3 to 6 units) beginning in late 1996. Maxwell acceptance tested these capacitors in accord with the NIF specification, and in some cases ran burn-in tests of 100 shots or more to verify quality. Additional characterization tests such as inductance and weight measurements were performed. Life testing was conducted at LLNL. After testing, units were returned to Maxwell for analysis.

IV. TEST RESULTS

A. Type A Designs

Three Type A models were prototyped and life tested. Each model has the same basic design, but the dielectric material thicknesses were varied. The life test data provided by LLNL for Model A1 is shown in Figure 3.

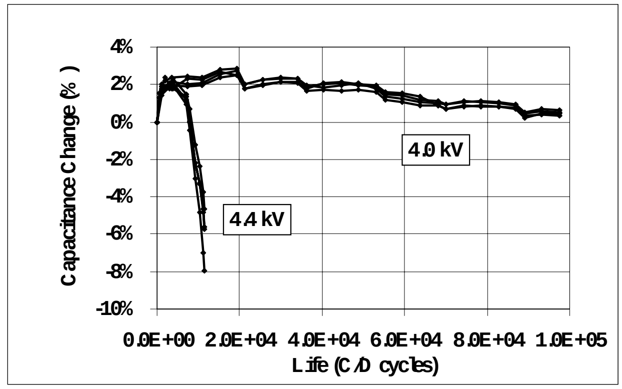

Figure 2. Life test results on Model C1 at two voltages.

Figure 4 shows the best fit lines for all three models, and the projected life for a fourth model using all three data sets. From this data, it was determined that the life of Type A capacitors under NIF life test conditions is given by the scaling equation:

$$L = L_o * (V/V_o)^{-18.335} \qquad (2)$$

where L is the life of the new design at some arbitrary

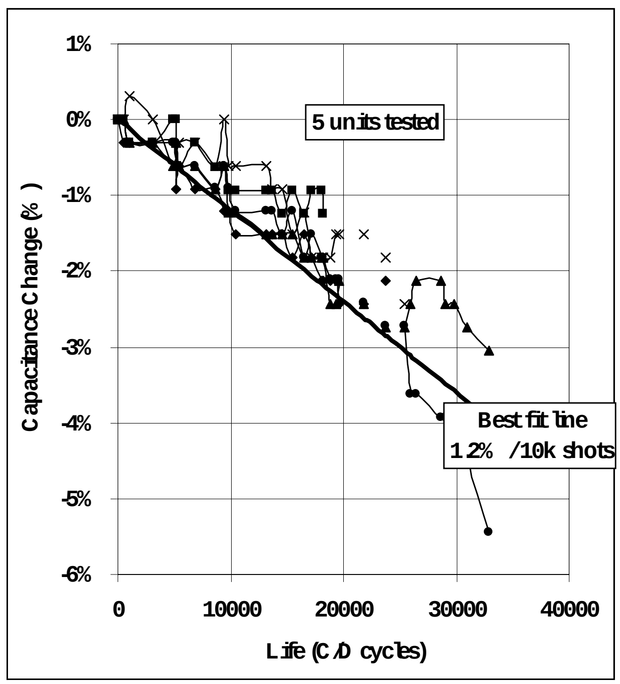

Figure 3. Life test data on Model A1.

percentage capacitance loss, L_o is the measured life at that value of capacitance loss, and V and V_o are the charge voltages of the new design and the reference design. The exponent value of –18.335 in Eq. 2 was the value which minimized the variance of the life predictions made from each data set.

Referring back to the ESR data in Figure 1, it can be seen that Type A capacitors have relatively high ESR

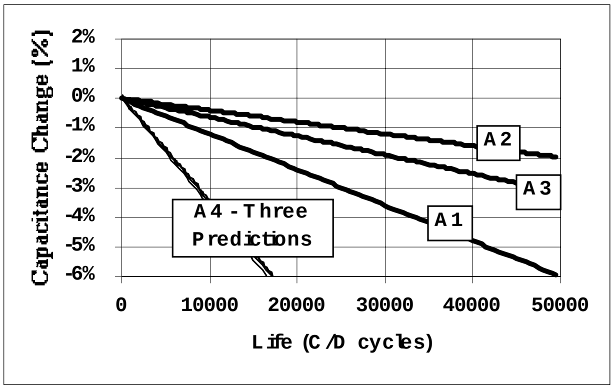

Figure 4. Fits to the life data on models A1, A2, and A3 and three nearly identical life predictions for a fourth model, A4.

compared to other designs under consideration. Maxwell's maximum ESR measurement on Model A1 was 11.0 milliohms (corrected for capacitance to the nominal 290 uF), and LLNL reported that the ESDR was in the range 10-18 milliohms.

The Equivalent Series Inductance (ESL) was measured on four units of Model A3 using the standing wave method and was between 183 and 199 nH, corresponding to a self-resonant frequency of about 20 kHz.

B. Type B Designs

A second design approach pursued by Maxwell involves a different dielectric and electrode. This approach is attractive due to reduced material cost, lower ESR (see Figure 4), and potentially reduced size and weight. Type B capacitor technology closely corresponds to the latest generation of defibrillator capacitors, now in mass production. However, the NIF requirement is actually more stringent than the medical defibrillator requirement in regards to the hold time at full rated voltage per charge cycle, the peak discharge current (especially under fault conditions) and the total number of charge/discharge cycles required. A modification of the metallized electrode was necessary to handle the higher current densities. Maxwell has recently supplied samples of two full-scale prototype designs, B1 and B2, to LLNL for life testing. Those results were not yet available at the time of this writing.

C. Type C Designs

A third approach which Maxwell has pursued is similar to Type B but involves a more sophisticated metallized electrode design. Early model capacitor results (see Figure 2) were promising, but an early scale-up to full-size prototypes did not pass Maxwell's Acceptance Test, due to termination failure on fault discharge testing. Significant improvements in the termination process used at Maxwell have been made since then, so this design approach remains viable.

V. SUMMARY

Maxwell has developed a reliable self-healing high voltage capacitor technology which is suitable for large systems such as NIF. This technology is similar to that used in earlier energy storage capacitor banks such as ARDEC's 52 MJ EM gun facility, but includes significant improvements. Maxwell has defined a new commercial series of capacitors, Series CM, based on this design. We consider these capacitors to be virtually "bullet-proof".

Further development of self-healing capacitors for NIF and for future requirements is continuing.

VI. ACKNOWLEDGEMENTS

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VI. REFERENCES

[1] For on-line information on this facility, see http://www.pica.army.mil/orgs/fsac/fsp/eacg/eacg.html

[2] N.C. Jaitly, et al, "Design of the 40 MJ Turnkey Power Conditioning System for the 60-Beam Omega Laser E-Stage and F-Stage Single Segmented Amplifiers", *1994 International Power Modulator Symposium*, Costa Mesa, California, June 27-30, 1994.

[3] "290 uF, 24 kV NIF Main Energy Storage Capacitor", University of California / Lawrence Livermore National Laboratory Specification NIF-0005095 Rev 0A, April 22,1998.