ZR MARX CAPACITOR LIFETIME TEST RESULTS [*]

David L. Smith[ξ]**, Mark E Savage, Gerold R. Ziska**[+]**, and Robert L. Starbird**[++]
Sandia National Laboratories, P.O. Box 5800, Dept. 1639
Albuquerque, NM 87185-1178 USA

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[*] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

[ξ] email: dlsmith@sandia.gov

[+] Ktech Corporation, 1300 Eubank SE, Albuquerque, NM 87123 USA

[++] Bechtel-Nevada, 316 East Atlas Circle, N. Las Vegas, NV 89030 USA

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Abstract

The ZR upgrade to the Z machine at Sandia National Labs (SNL) has a total output current requirement of at least 26 MA for a 100-ns standard z-pinch load. To accomplish this with minimal impact on the surrounding hardware, the existing Marx generator capacitors must be replaced with identical size units but with twice the capacitance. Before the 2005 six-month shut down and transition from Z to ZR occurs, 2500 of these capacitors will be delivered.

This paper summarizes the results of our lifetime testing of the selected General Atomics P/N 32896 11x14x25-inch, Scyllac-style insulator bushing, 2.65-µF, 100-kV, 30-nH, 35% reversal capacitor. We have completed lifetime tests with twelve capacitors at 100 kV and with fourteen capacitors at 110-kV charge voltage. The means of the fitted Weibull distributions for these two cases are about 17,000 and 10,000 shots, respectively. As a result of this effort plus the rigorous vendor testing prior to shipping, we are confident in the high reliability of these capacitors and have acquired information pertaining to their lifetime dependence on the operating voltage. One result of the analysis is that for these capacitors lifetime scales inversely with voltage to the 6.28 ± 0.9 power, over this 100 to 110-kV voltage range. Accepting the assumptions leading to this outcome allows us to predict the overall ZR system Marx generator reliability at the expected lower operating voltages of about 85 to 90 kV.

I. INTRODUCTION

In May of 2003 SNL began receiving the first shipments of a 20-month production run of 2500 new Marx generator capacitors from General Atomics Electronic Systems, Inc. (previously Sorrento Electronics, previously Maxwell Labs). This was the result of a major vendor evaluation and qualification effort. [1] We purchased a total of 30 evaluation capacitors and tested 45 units ultimately, completing the Marx capacitor testing of nine designs from five suppliers. We had the opportunity to work with CSI Technologies, Inc. of San Marcos, CA, ICAR Spa of Monza, Milano, Italy, Sorrento Electronics, Inc. of General Atomics Energy Products (GAEP) in San Diego, CA, Trench Limited (Haefely) of Scarborough, Ontario, Canada, and TPC of AVX in St-Apollinaire, France. Three technically qualified designs and one marginal design were identified. We selected a single supplier based on performance, cost, and production capability, and initiated our procurement strategy.

For the vendor evaluations and following tests we developed a very reliable automatic capacitor test facility capable of ~2,000 shots/month. [2] The automatic test facility can charge ten pairs of capacitors to ± 110 kV and discharge them at about 150-kA peak current and 35% reversal with a two to five minute cycle time. Each pair has a common gas switch and recirculating-liquid load resistor as seen in Fig. 1.

Figure 1. Capacitors, switch, and load in test stand.

One of our goals is to verify the voltage scaling effect on capacitor lifetime. We have used Weibull failure statistics and assumed a capacitor lifetime dependence on charge voltage ($\sim V^{-7.5}$) to help determine acceptable performance for the ZR facility. The Weibull distribution function is frequently used for electronic components having a probability of failure that increases with shot count, including high-energy discharge capacitors. [3] We wanted to establish as high a confidence as possible with these small sample sizes to predict the reliability of a full ZR population. A traditional power scaling guideline has been used by capacitor manufacturers to predict actual

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component lifetimes based on known sensitivities to the most important parameters: voltage, dielectric stress, reversal, stressed area, and ringing frequency. [4,5] One of its most general forms is shown by Eq. 1.

$$L=L_o(V/V_o)^{-4}(E(V)/E_o)^{-3.5}(Q/Q_o)^{-1.6}(A/A_o)^{-(1/\beta)}(f/f_o)^{-0.5} \quad (1)$$

For this expression, L represents the expected shot life after scaling; V is the capacitor operating terminal voltage; E is the dielectric electric field stress; A is the stressed dielectric area of the operating unit; β is the Weibull slope or shape factor; f is the ringing frequency of the operating unit; $Q=(\pi/2)[\ln(1/R)]^{-1}$ is the operating circuit quality factor; and R is the actual operating reversal (%). The symbols L_o, V_o, E_o, A_o, f_o, R_o, and Q_o are the baseline rated design parameters. The exponents were derived from a number of experimental databases. Note that the first two ratios in Eq. 1 may be combined for the case of a common dielectric system suggesting a strong sensitivity to voltage: $L/Lo=(V/Vo)^{-7.5}$. For the same components and circuit conditions, the other terms are equal to one. The next most sensitive parameter affecting capacitor lifetime is the reversal, and the frequency has a lesser effect. Providing that this scaling rule is accurate for our capacitors, we can accelerate testing by nearly a factor of two with 10% higher charge voltage (100 kV =>110 kV) or with 43% higher reversal (35% => 50%), or by nearly a factor of four with both.

Our vendor evaluation tests were all conducted at a charge voltage of 100 kV, but in order to predict the corresponding lifetime at the expected ZR operating voltage of 85 kV, we needed to confirm the voltage power scaling exponent for our specific capacitors. To reduce the total number of facility test shots and hopefully avoid exciting any new failure processes, we chose to compare the lifetime performance of two samples of the chosen General Atomics model tested at 100 kV and 110 kV.

II. 100-kV TEST RESULTS

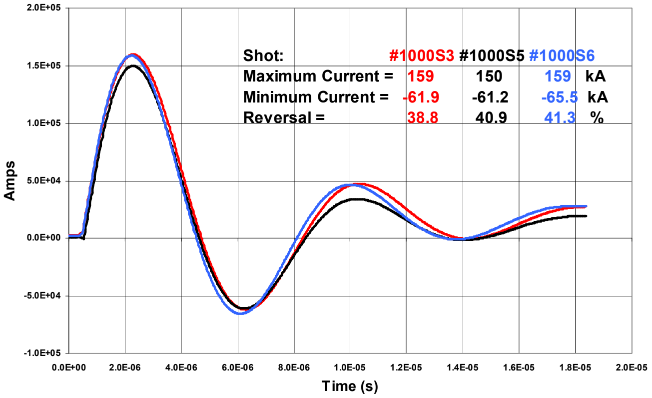

Figure 2. Currents for the top capacitors of stands 3, 5, and 6 for shot #1000 at 100 kV.

Figure 2 shows the current waveforms from three pairs of capacitors being discharged. There is always some waveform spread within a given shot due to small variations in the loads, switches, and calibrations. Typical peak currents were in the 150 to 160 kA range, and the reversals were 35 to 40%.

The 100-kV accelerated testing took seven capacitors to failure from a sample size of 12. The Weibull fit for the final 100-kV failure results suggested that the earliest loss was not a part of the dielectric wear-out mode. The Weibull fit using the Maximum Likelihood Estimator for the six 100-kV data points and with that earliest failure censored gives a typical result as seen in Fig. 3. The shape factor and mean generated by the Minitab v.14 software are 4.733 and 17,370, respectively. Note also that projecting the small sample data to the first failure for the full system of 2,160 capacitors corresponds to 0.046% and about 3,000 shots on the 95% confidence interval curve.

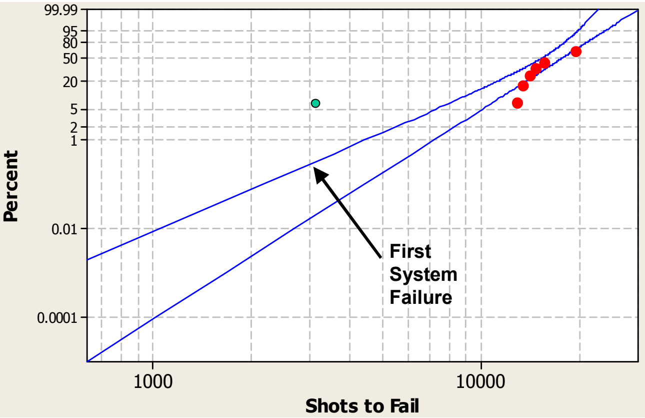

Figure 3. Weibull plot of 100-kV test failures.

III. 110-kV TEST RESULTS

The 110-kV accelerated testing took 13 capacitors to failure from a sample size of 14. The earliest two data points were questionable since those two capacitors did not fail in a manner similar to the rest, and one of them was likely damaged by a nearby external breakdown. If they were valid data, they would then suggest a bimodal failure mechanism and would have to be treated differently. Censoring these two earliest failures produced a good fit and a more typical Weibull slope, again using the Maximum Likelihood Estimator as seen in Fig. 4. The shape factor and mean are 4.439 and 10,435, respectively. Projecting the small sample data to the first failure for the full system at 0.046% corresponds to about 1,500 shots on the 95% confidence interval curve.

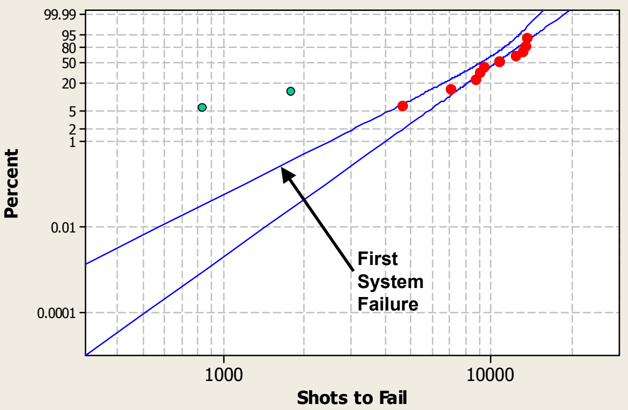

Figure 4. Weibull plot of 110-kV test failures.

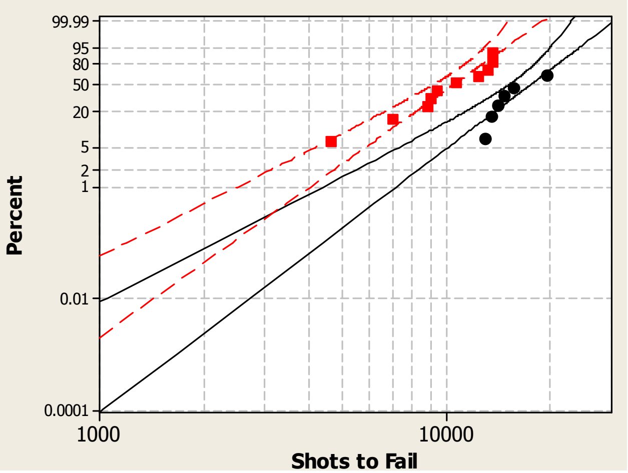

Figure 5. Plot of both 100-kV and 110-kV test results.

IV. POWER SCALING APPLICATION

Comparison of 100-kV and 110-kV capacitor lifetime data in the same plot of Fig. 5 emphasizes the translated means and similar slopes of the Weibull fitted curves. Using these two means and only the voltage terms of Eq. 1, the voltage exponent is calculated to be 5.35. This approach only relates a single point in the middle of these distributions and does not represent the rest.

Another approach that takes into account the whole distribution is demonstrated in Fig. 6. We have taken the fitted curves of Fig. 5 and plotted them as solid lines on a linear graph of Shots to Failure versus the Percent Failed. Comparing points on the two curves for common locations on the horizontal axis, we can generate the dashed line of exponent values that is plotted against the vertical axis on the right side of Fig. 6. The average of this rather flat line is 5.37, not much different than the previous approach with the means. This striking match works because the two test cases have very similar slopes in the Weibull plot. Significantly different slopes would result in a voltage power scaling that varies with the accumulated shots on the capacitors.

Since a voltage scaling power law between 6.0 and 7.5 was expected, the 5.37 result was considered low. A review of the 110-kV series waveform data showed that most of the peak currents, reversals, and ringing frequencies were reduced somewhat from the 100-kV test series. This suggested some power scaling contributions from the reversals and, to a lesser extent, frequencies.

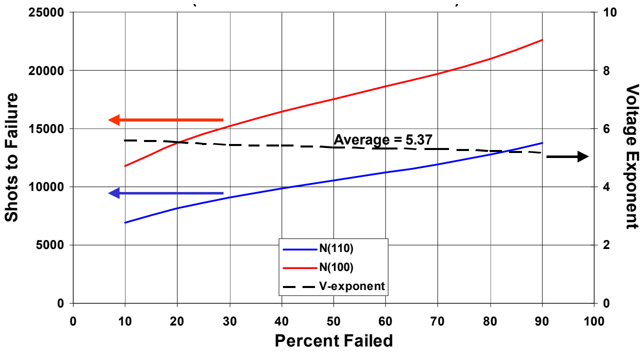

Figure 6. The voltage-scaling exponent is shown to be fairly constant throughout the two fitted distributions.

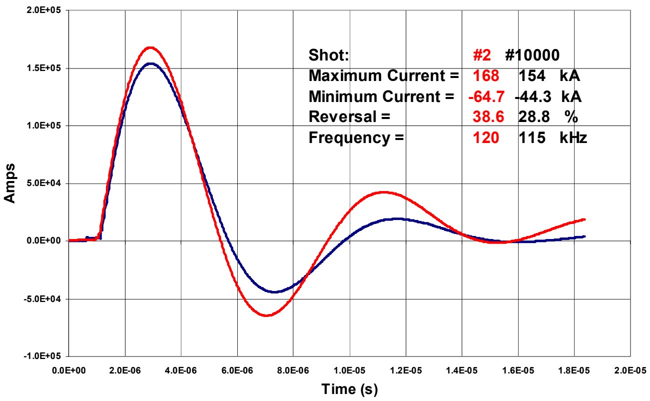

Figure 7. Currents for the top capacitors, stand six, shots #2 and #10,000 from the 110-kV test series.

The two waveforms of Fig. 7 approximately demonstrate the maximum variation between shots. The larger amplitude current trace shows the testing began at levels similar to the previous 100-kV test run. However, the parameters changed somewhat over the first couple of dozen shots to settle around the shape of the lower amplitude trace. This was due to intentionally adjusting the soap solution resistivity to keep the peak current near 150 kA.

The load resistor solution concentration changes and possible switch variations may have contributed to "long-term" drift over the testing process. Higher frequency, or daily, spreads may be related to temperature variations, electrical noise, and digitizer resolution, but these effects were not apparent during the steady reproducible automatic testing as indicated in Fig. 8. The graph shows a rather tight spread in the current waveforms that were selected from the beginning, middle, and end of a one-day run on 30 Jun 03.

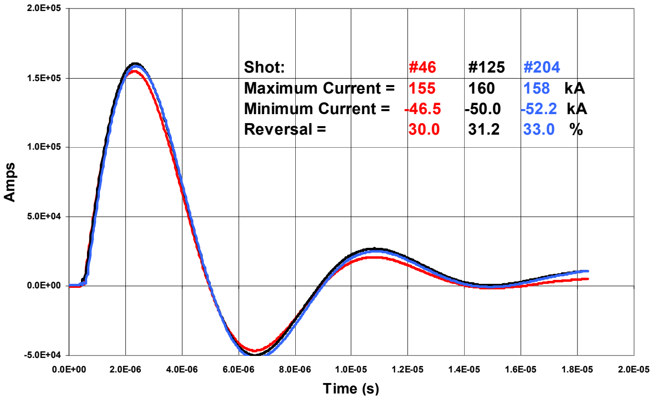

Figure 8. Currents for the top capacitors, stand six, shots #46, #125, and #204.

We propose that the effect of reversal and ringing frequency on lifetime may be translated into an equivalent voltage dependence. An example application of the traditional power-scaling rule in Eq. 1 requires that we trust the reversal and frequency term exponents of 1.6 and 0.5, respectively. Table 1 shows the percent change in lifetime due to them individually and together. The last column has the necessary increase in the voltage term exponent that would result in the same change.

Table 1. Matching Voltage to Reversal and Frequency

	Original Value	**New Value**	**Percent Change**	**Voltage Exponent To Match**
Frequency Effect:	**133 kHz**	**114 kHz**	**+ 8.0%**	**+ 0.47**
Reversal Effect:	**35%**	**30%**	**+ 24.5%**	**+ 1.35**
Frequency & Reversal Effect:	**133 kHz** **35%**	**114 kHz** **30%**	**+ 34.5%**	**+ 1.82**

Thus, if we can compensate the voltage exponent to include the effects of reduced frequency and reversal, then we may say that the actual value of the exponent is between 5.37 and 7.19 (i.e. 5.37+1.82). Another way to state this result is that 6.28 ± 0.9 represents the voltage power scaling for the lifetime of these particular capacitors in this range of test voltages. If we had chosen a higher original reversal than 35% in the table, the voltage power scaling would have been higher, but so would the error range.

V. CRITICAL ASSUMPTIONS

The validity of these results hinge on three primary assumptions, which we should not take for granted. 1) We can justify dropping early failure data because it is related to some other failure mechanism than the dielectric lifetime of interest (e.g. external shock, assembly errors, etc.). 2) We can choose the maximum likelihood estimator over the least squares Weibull fit methodology, since it allows more convenient and consistent comparison of the data sets. 3) The traditional capacitor lifetime power scaling for reversal and frequency is assumed to be approximately accurate. Keeping these in mind, we can conclude that the voltage power result is valid when stated with the large error bars.

VI. SUMMARY

The voltage exponent for predicting the General Atomics P/N 32896 ZR Marx generator capacitor lifetimes is: 6.28 ± 0.9 where the ± 0.9 range is the full spread accommodating the uncertainty in our assumptions and the probable effects of waveform reversal and frequency. Thus, we can predict the mean life for ZR capacitors operating at 85-kV charge:

$$L_{85} = L_{100} * (85/100)^{-6.28} = 48{,}200 \text{ shots}, \qquad (2)$$

where L_{100}=17,370 is the mean from our 100-kV test results. If we apply the same scaling to the earliest predicted 100-kV system failure at 3,000 shots, from extrapolating the 95% confidence interval down the Weibull scale of Fig. 3, we estimate that the first failure for a full ZR system population may be about 8,325 shots. Thus, a capacitor dielectric system failure at 85-kV charge operation should be very rare. The censored data may represent failure mechanisms different from the dielectric lifetime, but that limited information does not lend itself to any predictability.

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