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SUMMARY

Since 1971, LLNL has been pursuing inertial confinement fusion. The fusion program has built an ever increasing series of large Nd:glass lasers requiring considerable energy storage. Nova, a 300 kJ laser, under construction, will employ a 100 MJ capacitor bank. This greatly increased bank size drove the requirement for a high density capacitor. The Laser Fusion Program funded contracts with three energy storage capacitor producers: Aerovox, G.E. and Maxwell Laboratories, to develop higher energy density, lower cost capacitors.

A high-density, energy-storage capacitor, utilizing high density paper and caster oil as the dielectric, has been developed by Maxwell to meet this requirement. The evolution of the capacitor design which led to qualification and procurement of 6.5 MJ was based upon data from previous designs. The 12.5 kJ capacitors were developed and tested to define characteristic performance and life. From this program a capacitor which has an energy density of 71 joules per pound and a MTBF of 288 for a bank of 6,000 units and 10,000 shots was developed.

This paper covers Maxwell's approach to developing energy storage capacitors. Based on previous capacitor designs of 3 KJ, 5 KJ and 10 KJ, the final Nova 12.5 KJ capacitor evolved. At the outset of the Nova capacitor development program, a relatively new dielectric system, polypropylene-paper-DOP, seemed to show superiority in volumetric efficiency, life, and more importantly cost. However, as a result of studies performed at Maxwell, a high-density, energy-storage capacitor was developed utilizing new high-quality, high-density paper and caster oil as the dielectric. Test data have demonstrated that the Maxwell 12.5 KJ capacitor exceeds all LLNL's qualification requirements.

INTRODUCTION

The Argus and Shiva banks were built for the most part, with 20 KV, 14.5 μF, 3 KJ capacitors developed for the Sherwood Project.[1] Before Shiva was completed, LLNL in cooperation with Aerovox, Cornell Dubilier, Maxwell and Sangamo developed a 20 KV, 25 μF, 5 KJ capacitor which has a case size the same as the 3 KJ capacitor. Shiva uses 4 MJ of this capacitor type. For Nova, LLNL in cooperation with Aerovox, General Electric and Maxwell developed first a 20 kV, 50 μF, 10 KJ and then a 22 kV, 52 μF, 12.5 KJ capacitor. This paper discusses Maxwell's high-energy-density capacitor effort.

CAPACITOR REQUIREMENTS

The energy density of a capacitor is increased by increasing the dielectric stress. However, increased stress decreases capacitor lifetime. The lower cost and reduced volume of high-energy-density capacitors must be weighed against reduced lifetime. Table 1 presents the stress levels and nominal life spans for 3 KJ, 5 KJ, 10 KJ and 12.5 KJ capacitors.[2]

The 100 MJ Nova Bank will use about 6,000 high-density capacitors and salvage 25 MJ from Shiva. The system will incur approximately 10,000 total system discharges in its lifetime. An acceptable failure rate was chosen to be 2 to 3 failures per year. From these considerations, a preferred Weibull distribution for life performance of capacitors was generated. This distribution is graphed in Figure 1.[3]

Use of the Weibull distribution allows ranking of capacitors according to Mean Time Between Failure (MTBF). In Figure 1, the 2% failure level for the 50% confidence life is 10,000 shots. In a 6000-capacitor bank, 2% represents 120 failures. Therefore, it is expected that, on the average, failure will occur every 10,000/120 = 83.3 shots. This Mean Time Between Failure (MTBF) level and a slope of 1.3 was used to generate Figure 1. The slope was based on testing of small samples of similar capacitors.

High voltage, direct-current life is also an important capacitor parameter. The charge time for the Nova bank will be about 30 seconds. With this charge time and a dc life of over 1,000 hours, the failure rate due to time at voltage is reduced below that of pulsed life.

The performance goals of the high-energy-density capacitor were 1,000 hours of dc life, and a pulsed life giving a MTFB of 80 or more. The cost goal of this capacitor was five cents per joule.

3 KJ CAPACITOR

Maxwell's 3 KJ, 14.5 μF, 20 kV capacitor, having a case size of 7-1/4" x 14" x 24.31", was supplied to LLNL in 1974 and 1975. This capacitor was derived from the Sherwood Project 14 μF, 20 kV capacitor of the 1950's. The Sherwood 2.8 kJ capacitor had all parallel windings with four floating foil sections per winding, an interfoil voltage of 5 kV, and used a PCB impregnant. Two important changes were incorporated in the Maxwell design. The first and most significant was the change in impregnant to castor oil. This British technology was introduced to the U.S. by Dr. Alan Kolb, then at NRL, in the late 1950's. Castor oil was found to be a superior impregnant to PCB's especially under conditions of high voltage reversal and/or partial discharges, a condition common to energy storage capacitors. It produced a significant increase in the life of paper dielectric capcitors and became the standard and preferred oil. The second was due to the LLNL's requirement of two terminals isolated from the case. The design became a series-parallel combination with 1/2 of the winding, now with two floating foil sections, in series with the other half, or a simple up-and-back construction. The up-and-back configuration is common to all later Shiva designs. Maxwell's 3 KJ capacitor was a five layer design using 35 ga. foil.

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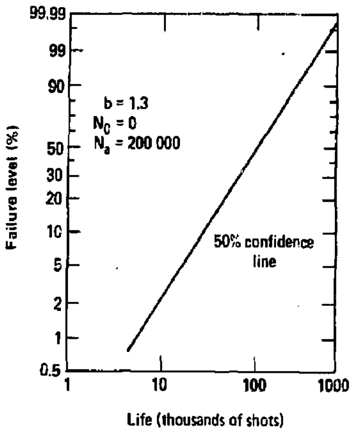
STRESS LEVELS AND NOMINAL LIFE SPANS OF CAPACITORS

TABLE 1

	14.5 μF	25 μF	50 μF	52 μF
Operating voltage (kV)	20	20	20	22
Energy storage (kJ)	2.9	5	10	12.5
Number of series sections	4	2	2	2
Voltage per section (kV)	5	10	10	11
Operating stress (kV/mil)	2,083	2,564	3,350	3,333
Dielectric type	Paper/Castor Oil	Paper/Castor Oil	Paper/Castor Oil	Paper/Castor Oil
DC life (h)	2,000	1,200	2,500	1,000
Pulsed life[a] (shots)	10^6	500,000	200,000	200,000

[a]Nonreversal (3 kA)



Preferred Weibull for Nova Capacitors

Figure 1

The life of these units far exceeded the requirements of a large glass-laser system, $>10^5$ discharges at 80% voltage reversal and $>10^6$ at 20%. Maxwell produced about 7,200 3 kJ capacitors for Argus and Shiva. Although there is not an accurate failure percentage figure, approximately 0.17% of these 3 kJ units failed in over 1,000 full system shots.

5 kJ CAPACITOR

The 5 kJ, 25 μF, 20 kV capacitor increased energy density by 72% and was inspired by a Maxwell design developed for General Atomic in 1970. A 100 μF, 10 kV, 5 kJ capacitor, based on life tests from an internal R&D program, aroused the interest of LLNL while on a life test in 1973. Reconnected in the standard up-and-back configuration, this capacitor became the first 25 μF, 20 kV unit. It used single section windings with an interfoil voltage of 10 kV and six layers of paper with a stress of 2,564 V/mil. It also used 35 ga. foil and was one inch taller than the 14.5 μF capacitor. The life of this unit was $>10^4$ discharges at 85% VR and $>5 \times 10^5$ discharges at 20% VR, still exceeding the requirements of Shiva's actual usage with acceptable reliability.

DEVELOPMENT CONSIDERATION FOR NOVA CAPACITOR

In late 1977, the capacitor requirements for Nova were becoming more defined. The objective was to increase the capacitor energy density, thereby reducing cost, while meeting more defined life and reliability requirements. With the system voltage set around 20 kV, 10 kJ and possibly 20 kJ capacitors looked like a reasonable goals. Performance specifications made extended foil construction necessary and the size constraints of the capacitor bank modules set the case size.

Initially, the idea of exploring a new dielectric system, polypropylene/paper, impregnated with di-octyl-phthalate (DOP), was proposed as a means of meeting the performance goals while reducing the capacitor cost. This dielectric system, specifically the impregnant, had been developed for ac capacitors, as a result of the ban on PCB's. Initial test data on similar type capacitors made it look promising.

LLNL awarded study contracts to Maxwell, as well as Aerovox and General Electric, to explore various methods of achieving higher energy density. The original performance specifications were:

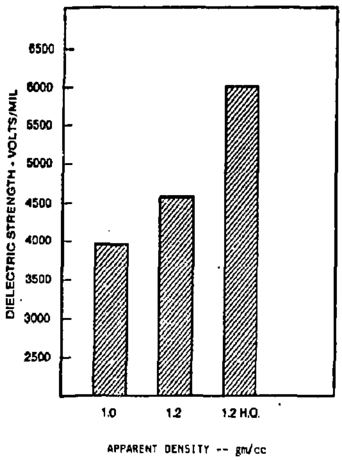
Pulsed life: 200,000 cycles, non-oscillatory discharge

DC life 2,000 hours @ 22 kV

High voltage rev. - 500 cycles

Maxwell evaluated the proposed polypropylene/paper/DOP system as well as the more traditional paper/castor oil system. Both systems appeared to have definite advantages, as well as disadvantages.

Dielectric strength was one characteristic that was considered fundamental in determining the design. Polypropylene film has an average breakdown strength of approximately twice that of the standard Kraft capacitor tissue; however, recent developments and improvements in the manufacturing of capacitor paper have resulted in higher-density papers developed for energy storage capacitors. These high-density, high-quality papers have an increase of approximately 50% in breakdown strength over standard 1.0 density paper as shown in Figure 2. This permits the use of higher stresses in the capacitor, which enables a reduction in the thickness of the dielectric needed or provides improved reliability.



Dependance of Breakdown Strength Versus Density

Figure 2

The stress relationships for the two systems were taken into consideration. Because the dielectric constant of the paper/castor oil system is approximately double that of the paper/poly/DOP system, the resultant stress on the polypropylene is over 1.8 times the stress that is on the paper of an all paper design.

The two impregnants were also evaluated. After comparing castor oil and DOP, it was decided that castor oil, being less susceptible to contamination was the most likely candidate. DOP is also extremely sensitive to moisture which made it less attractive to use with an all paper capacitor.

Two conceptual designs were made; one using the high-density, high-quality paper impregnated with castor oil and one using the polypropylene film, paper and DOP. The paper/caster oil design had five layers of paper while the equivalent polypropylene/paper/DOP design had two layers of film with a layer of paper between them. Considering the greater number of layers, the reliability of the paper/castor oil system appeared to be higher.

Cost analysis of the two designs confirmed that a high quality paper/castor oil capacitor could be produced at a competitive cost with a paper/ polypropylene/DOP capacitor. The paper/castor oil capacitor would have nearly the same unit volume, energy density, and operate at 66% of the dielectric stress of the paper/polypropylene/DOP capacitor. After the study was completed, and discussions held with LLNL, an agreement was reached that Maxwell would produce and test a high-density, high-quality paper/castor oil capacitor as an alternative to paper/polypropylene/DOP capacitor.

10 kJ CAPACITOR

The resulting Maxwell 10 kJ, 50 μF, 20 kV capacitor had an average capacitance of 51 μF, while using the same case size as the 14.5 μF unit. This was an increase in energy density per cubic inch more than double the 25 μF capacitor and nearly 3.5 times the 14.5 μF unit. This design used five sheets of paper between foils with a dielectric stress of approximately 3,350 volts/mil. Like the 5 kJ unit this capacitor used single section windings connected up-and-back with an interfoil voltage of 10 kV.

To get the 10 kJ's into the 14.5 μF case size and reduce costs, it was necessary to use 25 ga. foil. Degradation of 25 and thinner gauge foils in the body of capacitor windings was observed by LANL during tests on 170 μF, 10 kV capacitors under low current, low voltage reversal conditions similar to Shiva[4]. The high current densities present in the 170 μF capacitors was the probable cause of the foil degradation, but degradation was not observed in paper/castor oil capacitors until after 500,000 discharges. LANL found this degradation to be more prevalent in paper/poly/DOP capacitors. The other problem, termination failures when using thin foils, was noted on capacitors with >5 kJ in the mid 1970's.[5] Because of improvements in swaging (soldering) techniques and the material used in terminating the extended aluminum foil this is no longer considered a problem. With LLNL only requiring 200,000 shots, using 25 ga. foil was not considered a problem and did not affect the 10 kJ test results.

During the manufacturing of this unit in early 1978, both Maxwell and LLNL became concerned over its dc life. Because of the long charging time required to bring such a large bank as Shiva-Nova up to voltage, it was realized that the dc life could be a limiting life factor. A calculation using an accepted dc life formula with standard paper/castor oil data, produced a life of only 389 hours. This was not adequate for the Nova Program and, as a result, Maxwell and LLNL began dc testing at 20 kV. One unit received a total of 2,500 hours of dc voltage without failure.

Obviously, the dc formula and/or data no longer applied. When LLNL later upgraded to 12.5 kJ at 22 kV, one unit was tested for 2,570 hours at 23 kV, followed by 10^5 discharge shots at 20 kV without failing. Three other 10 kJ capacitors received only discharge shots at 20 kV. Further testing was halted because of the changeover to 12.5 kJ units. There were no failures during these tests and the results are listed below:

Number of Capacitors	DC Hours	Charge/Discharge Cycles at 10% VR
1	2,500 @ 20 kV	None
1	2,570 @ 23 kV	108,00 @ 20 kV
3	None	259,000 @ 20 kV

12.5 kJ CAPACITOR

In July of 1978, before the 20 kJ, 20 kV capacitors were manufactured, LLNL expressed the desire to change to 12.5 kJ, 22 kV capacitors. Due to favorable test data on the 20 kJ prototypes it was felt that more energy could be obtained by increasing section voltage from 10 kV to 11 kV and possibly still meet performance goals.

A design resulted using the 11 kV sections but keeping the stress nearly identical to the 10 kJ. This design was the standard up-and-back design common to previous Shiva capacitors. It had a dielectric stress of 3,333 volts/mil, 25 ga. foil for the electrodes and .75" margins. By staying with the same dielectric stress, the volume of the capacitor increased approximately 25%.

PROTOTYPE TESTS

Ten prototype capacitors were shipped to LLNL and underwent a test series. Two capacitors were put on dc life test at 22 kV and were removed after 2,500 hours with no failures. A third capacitor was dc life tested 2,000 hours at 22 kV and 500 hours at 24 kV with no failure. In addition, one of the capacitors with 2,500 hours dc was put on discharge test and failed after 80,900 shots. Other failure data are as follows:

Number of Capacitors	DC Hours	Charge/Discharge Cycles at 10% VR
2	2,500 @ 22 kV	1 - none 1-80,900
1	2,000 @ 22 kV & 500 @ 24 kV	None
1	None	90,000 @ 20 kV & 95,000 @ 22 kV
1	None	107,000 @ 20 kV & 1,500 @ 22 kV
1	None	189,000 @ 22 kV
1	None	257,000 @ 22 kV*
1	None	4,943**

* Did not fail.
** 85% reversal.

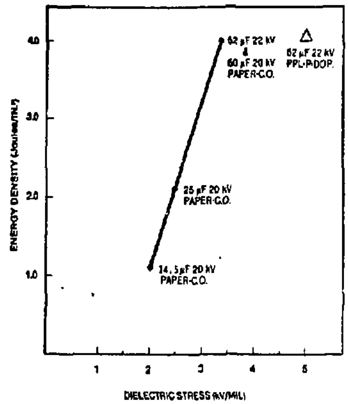
FAILURE MODE ANALYSIS

Following the test series an investigation of the failures was made with hope of identifying any design deficiencies that could be corrected. The high reversal failure was examined revealing a margin flashover. Examinaton of the windings showed extensive foil damage in the outer turns of the windings. This was evident on the flattened portion of the end windings and on the radiused portions of the other windings. Although this was not the failure mechanism of this capacitor, had the margins held, it most likely would have been. This extensive burning and foil degradation probably can be attributed to pinholes in the foil. During high peak current discharges, the current density becomes sufficiently large to arc across the pinholes. The resultant byproducts and damage caused by the arc will eventually lead to failure. This phenomenon was first noticed on capacitors tested by LANL[6].

Examination of the other capacitors revealed the same failure mode as the high reversal failure. All had flashed across the margin, causing the other series section to fail due to over-voltage. A close examiniation of the windings revealed damage to the foil starting to appear on the winding radius, again predominant on the outer few turns. The foil damage, though, was nowhere near as extensive as on the high reversal failure.

As a result of the failure analysis, it was determined that the margins were not adequate for the increased pad voltage and the foil thickness would have to be increased to eliminate the erosion problem. The final 12.5 kJ design incorporated an increase in the foil thickness to 30 ga. and a increase in the margins to .875". In order to compensate for added foil thickness and the increased margins without losing capacitance, it was necessary to increase the capacitor length by .875 inches. This put the final capacitor dimensions at 8.38" x 14.0" x 27". The dielectric thickness remained the same.

The energy density versus dielectric stress tradeoff as the capacitors evolved from 3 KJ to 12.5 KJ is summarized in Figure 3. The final 12.5 KJ design operates at nearly the same stress as the 10 KJ design. Maxwell's proposed paper/poly/DOP design is also shown for comparison.



Dependance of Dielectric Stress Versus Energy Density
Figure 3

The final design was qualified for Nova by the following test program.

TEST PROGRAM

To qualify a capacitor build for use on Nova, a sample of 35 capacitors of each build were subjected to the following tests.

The first test was the pulse discharge test. Thirty of the units were tested to 20,000 shots or failure. The remaining five were tested to 100,000 shots or until 3 of 5 failed. Results of this testing were analyzed using Weilbull statistics.

The pulse discharge test conditions were:

Charge voltage	24 Kv
Charge time	12.5 sec.
Hold time	2.5 sec.
Discharge peak current	5 kA
Discharge voltage reversal	10%
Stabilized external temp.	25 ±5 degrees C

The pulse tests were operated at 24 kV for two reasons. First, up to 20% of the capacitor laser shots may occur at 24 kV. Second, testing at 24 Kv gains a factor of two acceleration according to the eight power scaling law for life.

Two of the capacitors which survived the 20,000 shot pulse discharge test were subjected to 1,500 high reversal shots. The purpose of this test was to insure that the solder connections inside the capacitor were adequate.

The conditions for the reversal test were:

Charge voltage	22 kV
Charge time	22.5 sec.
Hold time	2.5 sec.
Discharge peak current	60 kA
Discharge voltage reversal	85%
Stabilized external temp.	25 ±5 degree C

The criteria for acceptance was that both capacitors had to survive 500 shots.

Two other capacitors which survived the 20,000 shot pulse discharge test were placed on a dc life test. These units were charged to 24 kV and held there for 1,000 hours. The criteria for acceptability was that the two units had to average 500 hours life at voltage.

Each failed capacitor was autoposied and the failure modes identified. In addition, the capacitors were carefully examined for quality of workmanship.

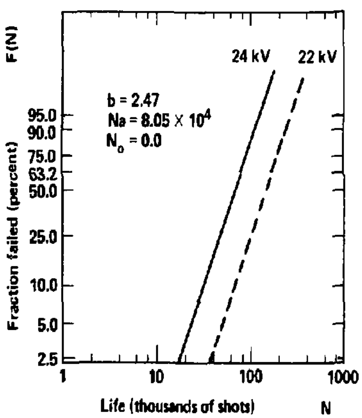
TEST RESULTS AND ANALYSIS

Test results for the Maxwell high energy density capacitor are summarized below[7]:

35 total units tested; $C_{avg} = 53.37\ \mu F$.

2 units - dc tested 1,000 hrs. at 24 kV	Pass, no failures
2 units - ring test 1,500 shots at 22 kV	Pass, no failures
20 units - pulse test 20,000 shots	No failures
2 units - pulse test 64,877 shots	No failures
1 unit - pulse test 7,698 shots	Failed
1 unit - pulse test 47,775 shots	Failed
1 unit - pulsed test 64,877 shots	Failed

Using the above data, a maximum-likelihood estimate Weibull distribution was generated (Figure 4). Substituting $b = 2.47$, $Na = 16.1 \times 10^4$, and $N_0 = 0.0$ into the Weibull distribution function.



Weibull Plot for 12 KJ, Paper/Castor Oil Capacitor

Figure 4

$$F(N) = 1 - \exp -(N-N_0)/(N_a-N_0)^b \qquad (1)$$

where F = fraction failed
N = shot life
N_0 = minimum life expectancy
N_a = characteristic life
b = Weibull slope

gives a fraction failed at 10,000 shots of 0.58% and a MTBF of 288 for a bank of 6,000 units and a 10,000 shot life at 22 kV. This far exceeds LLNL's goal of a 83.3 MTBF.

1. K. Whitham, M. M. Howland and J. R. Hutzler, "High Density Energy Storage Capacitor," Proceedings of the 8th Symposium on Engineering Problems of Fusion Research, San Francisco, CA; November 1979, Vol. 2, pp. 714-718.

2. "Laser Program Annual Report -- 1979," UCRL-50021-79, Livermore, CA; March 1980, Vol. 1, pp. 2-94.

3. Ibid.

4. G. P. Boicourt and E. L. Kemp, "A Newly Discovered Failure Mode in High Energy Density Energy Storage Capacitors," LASL Report.

5. J. R. Hutzler and W. C. Gagnon, "Development of a Reliable, Low-Cost, Energy-Storage Capacitor for Laser Pumping," Proceeding of International Conference on Energy Storage, Compression, and Switching, Torino, Italy, November 1974.

6. Op. Cit. 4.

7. B. T. Merritt and K. Whitham, "Performance and Cost Analysis of Large Capacitor Banks Using Weiball Statistics and MTBF," Proceedings 3rd IEEE International Pulsed Power Conference Albuquerque, NM; June 1981.