

# HIGH ENERGY, LOW INDUCTANCE, HIGH CURRENT FIBERGLASS ENERGY STORAGE CAPACITOR FOR THE ATLAS MACHINE MARX MODULES

by

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## ABSTRACT

The Los Alamos National Laboratory's Atlas Marx design team envisioned a double ended plastic case 60kV, 15nH, 650kA, energy storage capacitor. A design specification was established and submitted to various vendors. Maxwell Energy Products drew from its development of large fiberglass case, high voltage, low inductance "FASTCAP" capacitors manufactured for Maxwell Technologies' ACE II, ACE III and ACE IV machines.

This paper discusses the LANL specification and Maxwell Energy Products' successful design, Model No. 39232, 34.1 uF, 60kV, 13 × 29 × 27", the only capacitor qualified by LANL for the 23 Mega Joule Atlas application. Maxwell's past experience in this type of capacitor will be covered. The performance data will be reviewed and the life test data compared to the original calculated design life. Challenges included Maxwell's "keep it simple" design goal which was maintained to minimize the effort required to create and manufacture a nearly 600 pound capacitor.

## I. ATLAS CAPACITOR SPECIFICATION

The LANL basic goals were adhered to with few variations during the development period running from late 1993 to 1997. Through this period of about four years, the mounting system, current and life requirements were refined. These changes and the 1998-production specification for Maxwell's Atlas Capacitor, Model No. 39232 are in Table 1.

The inductance of this capacitor has always been important. A problem exists over the measuring method and interpretation of the measurement. The final specification value of ~22nH is based on Maxwell's measurements on Model No. 39232 using a low inductance single channel switch. Measurements made at LANL were interpreted to be less than 20nH. For production purposes, LANL built two measuring jigs,

they add some inductance to the measurement, but allow the measurements to be duplicated at both Maxwell and LANL. These measurements are used for comparative purposes.

## II. MAXWELL'S PAST EXPERIENCE

Maxwell has been manufacturing low inductance plastic case capacitors for Marx generators since the late 1960's. Beginning in 1986 the FASTCAP Program established a goal to develop high energy, low inductance, self-supporting, fiberglass case, Marx capacitors, which could be stacked up without racks and supports. The initial full size capacitor was a complicated 1200 lb. behemoth, Model No 39089, rated at 11.1uF 120kV (14.75 × 34.75 × 51" long). This unit was coupled with Maxwell's low inductance multi-channel rail gap and used in ACE II. These units were basically two capacitors wrapped into one case; to be discharged in a series connection with a switch mounted tightly to one end. The next generation of FASTCAP was a 4.2 uF, 180kV version, which would eventually require a different switch. This higher voltage unit exceeded the voltage withstand capability of the rail gap switch and would deliver more current than could be managed by a higher inductance single channel switch. The use of a smaller, lower energy design permitted a reduction of Marx stage currents to levels manageable by a single channel switch. This unit, called the 1/4 sized unit, Model No. 39156, 1.3 uF 180kV (14.7 × 19.2 × 37", 530 lbs.) was used in both ACE III and ACE IV. Low inductance was achieved by using more of these 1/4 size units in parallel.

Like the FASTCAP and many other high current capacitors, Maxwell's Atlas unit Model No. 39232, uses an all high density paper - castor oil dielectric system, with extended foil construction

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Table 1. Atlas Capacitor Specification.

| Atlas Capacitor Specification |                 |                 |                 |                       |                  |
|-------------------------------|-----------------|-----------------|-----------------|-----------------------|------------------|
| Item                          | 1993            | Q1 '94          | 1996            | 1997                  | 1998             |
|                               | Projection      | LANL Spec       | Maxwell Spec    | LANL Spec             | Final Spec       |
| Capacitance (uF):             | 33.4 +/-<br>10% | 33.5 +/-<br>10% | 33.5 +/-<br>10% | 34.1 -<br>3%,+7%      | 34.1 -<br>3%,+7% |
| Voltage (kV):                 | 60              | 60              | 60              | 60                    | 60               |
| Energy (kJoules):             | 60.1            | 60.3            | 60.3            | 61.4                  | 61.4             |
| Voltage Reversal              |                 |                 |                 |                       |                  |
| Normal                        | 15%             | 15%             | 15%             | 15%                   | 15%              |
| Fault                         |                 | 25%             | 25%             | 25%                   | 25%              |
| Peak Current                  |                 |                 |                 |                       |                  |
| Normal                        | 500kA           | 450kA           | 330 kA          | 330kA                 | 330kA            |
| Fault                         |                 | 650kA           | 650kA           | 660kA                 | 750kA            |
| Inductance:                   | 20nH            | 25nH            | 25nH            | 20nH                  | ~22nH            |
| Dissipation Factor            |                 |                 |                 |                       |                  |
| @ 120 Hz                      |                 |                 | 0.65%           |                       | 0.65%            |
| @ 10 kHz:                     |                 |                 |                 | 2.50%                 | 2.50%            |
| Design Life @ 95 % Survival:  |                 | 1000            | 2400            | 2400                  | 2400             |
| Failure Rate @ 1000 Shots     |                 |                 |                 | <2.7x10 <sup>-5</sup> | -                |
| Case Size (H x W x L):        | 14 x24 x30"     | 13 x23 x28"     | 13 x29 x27"     | 13 x29<br>x27.07"     | 13 x29<br>x27.1" |
| Case Wall at Interface:       | .25"            | 0.125"          | 0.13            | 0.14                  | 0.14             |
| Min. Case Withstand           |                 | 80kV            | 70kV            | 70kV                  | 70kV             |
| Electrode Terminal:           | 2" x 20"        | 2" x 21"        | 2" x 14"        | 2" x 18"              | 2" x 18"         |
| Mounting:                     | None            | None            | Side Rails      | Side Rails            | Side Rails       |

### III. PERFORMANCE DATA

Two vendors were finally chosen to submit capacitor for qualification. Maxwell began building units in 1996 and the majority of testing was done in 1997.

There were two groups of Maxwell test units with clearly different results. The first group of prototypes suffered from erratic test results caused by incomplete impregnation. The first two test units from this group were subjected to case quality problems (leaky case walls) and had been re-cased at least once. One would have expected this to have cause more harm than good, but these two provided the better results, 2097 and 1514 full voltage charge/discharge cycles. The fresh units put on test later faired worst. It was determined from this early results, that more impregnation or post curing was necessary to simulate the "parking lot effect" and obtain the full design life of these Atlas capacitors.

A clear and dramatic difference was observed going forward. With a combination of extra time and/or processing all the test units falling into the second group, exceeded 4000 cycles at the normal operating parameters of ~300 to 330 kA and 13 to 18% voltage reversal. See Table 2. Two units had 300 additional shots under the fault conditions of ~700kA and 25% voltage reversal and 3 shots at ~70% reversal at ~600kA without failure. Only two units were actually tested to failure out of these 11

test capacitors. The 300 discharges at 25% voltage reversal, the fault conditions, were equivalent to 653 at the normal operating parameters. These values were used in the calculations found in the following Design Life section.

Table 2. Model No. 39232 life Data.

| LANL Qualification Life Test Data   |              |                   |                  |                   |
|---|--------------|-------------------|------------------|-------------------|
| No. of Units  | Failed/ Good | Normal C/D Cycles | Fault C/D Cycles | Normali zed Total |
| 1   | Failed       | 8150              |                  | 8150              |
| 1   | Good         | 7600              |                  | 7600              |
| 1   | Failed       | 6200              |                  | 6200              |
| 2   | Good         | 4000              | 300              | 4653              |
| 6   | Good         | 4000              |                  | 4000              |
| Normal Discharge: ~330kA 15% Voltage Reversal<br>Fault Discharge: ~700kA 25% Voltage Reversal |              |                   |                  |                   |

### IV. DESIGN LIFE

The lack of failures makes utilization of good life data difficult. The Atlas design goal is 2400 charge/discharge

cycles with 95% survival with a 1997 specification goal of a  $2.7 \times 10^{-5}$  probability of failure at 1000 shots. If all 11 capacitors were considered failed, an analysis using Maxwell's Weibull Analysis Capacitor Reliability Program, would give a 95% survival of >3050 shots, but only a  $13.8 \times 10^{-5}$  probability of failure (or .0138%) at 1000 c/d cycles. This is still less than one failed capacitor out of a bank of 384 units. This doesn't take into consideration early random failures caused by defective units. LANL applying a "reasonable assumption" to nine data points (estimating end of life) obtained a failure rate of .07%. LANL also looked at a "worst case" analysis, this produced a 1.75% value or 7 capacitor failures by 1000 c/d cycles. Using the same data points (assuming all failed), the LANL values were re-calculated using the Weibull Analysis Program. The resulting values are 3479 c/d cycles @ 95% with .0129% failed a 1000 c/d cycles and for the "worst case", 2930 and .0295% respectively.

Maxwell's design life calculations are based on the Weibull analysis of Sandia National Laboratory [1] life tests on a similarly designed 3uF 100kV capacitors. The calculations took into account a wide range of factors, dielectric stress, interfoil voltage, voltage reversal, ringing frequency and active area. The following was presented to LANL in December 1997 while the life tests were in progress.

The analysis of the data, shown in Table 3 is a comparison of the Maxwell capacitors against the requirements of the 1997 Specification in two ways. First the data is compared as evaluated by SNL. A second evaluation was done using Maxwell's Weibull Analysis Capacitor Reliability Program.

| Atlas Capacitors Weibull Statistical Analysis |   |                         |          |
|---|---|-------------------------|----------|
| Item  | Shots with 95% Survival   | Failure Rate @ 1k Shots | See Note |
| Specification                                 | 2400  | $2.7 * 10^{-5}$         | 1        |
| SNL   | 3431  | $5.4 * 10^{-7}$         | 2        |
| Maxwell                                       | 2833  | $6.6 * 10^{-5}$         | 3        |
| Note  |   |                         |          |
| 1   | The life requirement specified by LANL  |                         |          |
| 2   | The life expectancy based on SNL's data for median value                            |                         |          |
| 3   | Maxwell calculations using the SNL data and Maxwell's Capacitor Reliability program |                         |          |

Table 3. Design Life Calculations.

The Maxwell analysis of the same data evaluated by SNL shows a slightly lower life expectancy. Both

methods of analysis indicate that the capacitors exceed the requirements of the specification.

The calculations are based on a referenced life for the SNL and Maxwell calculation of 6249 and 5432 respectively. The reference life is generated by the Weibull analysis. This multiplied by the acceleration factors of 0.5491 and 0.5216 resulting in the life at 95% survival listed in Table 3 of 3431 and 2833 respectively.

For the SNL and Maxwell analysis of the data,  $\beta$  is 9.3 and 6.4 respectively.

## V. CHALLENGES

The challenges were noble ones, build a 600 lb low inductance, high current, very reliable capacitor, put it in a thin walled fiberglass box to be held by its edges, make it capable of supporting a large rail gap switch and necessary hardware, and "keep it simple".

### A. The Case

The FASTCAP cases of the past had heavy walls and large outside fitting end covers that were bolted on at first, then later epoxied. These large end covers were the main part of the self-supporting system and the terminals were fed through them.

The Atlas case needed to be thin walled on at least one side. Two units are assembled together thin side to thin side to minimize inductance. Each pair of units with switch and hardware is suspended on the 1/2 wide side rails of the bottom capacitor. The allowable space between units must be minimized, to do that, the end covers with terminals had to be flush with the case. To keep the assembly simple, it was easier to slip the case over the capacitor than push >400lbs into this thin walled box. So the end plates or covers had to seal to the inside of this tube like case.

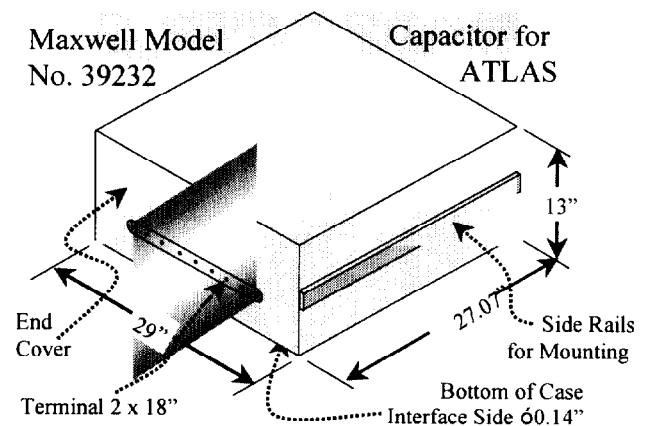


Figure 1. Maxwell's LANL Qualified Atlas Capacitor.

### B. Handling

The winding assemblies are made in two parts; separately they can be moved and turned by one person. Once these stacks are coupled they are placed on carts, where the assembly is continued. The case is then

dropped over the assembly. The capacitor is flipped, placed back on the cart and the top assembly completed. The capacitor is rolled to the epoxy area, sealed, clean and moved to the impregnation room. After impregnation the capacitor is placed back on the cart for easy movement through leak check, post curing, cleaning and finally to test.

By keeping the design, assembly and handling processes simple, with the help of tooling or equipment, only one person is required to handle this 600 lb. Atlas capacitor at most manufacturing stations.

### C. Quality Control

Maxwell Energy Products is certified to ISO 9001. Steps are taken throughout the process to control quality. The paper must meet tight minimum electrical standards before it is shipped. The thickness is marked on each roll so the setup of the machine will yield capacitors stacks within a reasonable range of height and capacitance. Each winding is electrically tested, dry pot tested, before being stacked. The height of each stack is recorded on an individual traveler that also contains the winder's name and material lots used. Each stack is permanently serialized and passed to assembly. After the stack is swaged the capacitance is read and recorded, then they are sorted to maintain tight capacitance and fit tolerances.

The cases are pre-tested dry to 50 kV before they are prepared for assembly. This has proven more than sufficient screening, no capacitor case passing this test has failed the 70kV minimum dielectric withstand test.

The travelers from the stacks are combined and attach to a capacitor traveler and the case serialized. This traveler is maintained throughout the balance of the manufacturing process and stored for reference. The capacitors are group by run number (impregnation lot number), these units are processed together through drying and impregnation. After leak testing and post curing the units are moved to test.

100% of the units are high voltage tested to 66 kV for one minute and then given 10 burn-in shots at 60 kV, typically 350 to 400 kA at 20 to 25% voltage reversal. The inductance is measured on stacked pairs (thin sides facing each other) using the LANL supplied jig. A sample from each lot is tested at 70kV "terminal to case"; the capacitors are placed under oil onto an aluminum plate. An insulation resistance measurement is also made on a sample from each impregnation lot.

After final mechanical checks and Quality Control acceptance the units are crated in individual boxes and identified with a copy of that capacitor's label. Traceability is maintained throughout manufacturing.

## V. SUMMARY

In 1993 Los Alamos National Laboratory began a quest for a fiberglass "FASTCAP" like capacitor, equivalent to two standard large metal case capacitors. That could be assembled into modules with lower inductance. Maxwell

Energy Products had past experience manufacturing large fiberglass capacitors for ACE II, III and IV, this provided a strong background and starting point. Maxwell's design life calculations and inductance experiments showed that LANL's goals could be met. LANL finally picked two vendors to supply test prototypes.

Maxwell began making life test prototypes of Model No. 39232 in 1996. Maxwell's design demonstrated a "soft failure" mode during the life tests. This capacitor fails short without violence explosion, a major advantage over standard metal cased capacitors. After a disappointing start, eleven fully impregnated test capacitors reach or surpassed 4000 charge/discharge cycles. The problem became the time and cost of testing units to failure, for only two units had actually failed, one at 6200 and the other after 8150 shots.

Two different calculated design life values were submitted to LANL in 1997, both 3431 and 2833 c/d cycles with 95% survival exceeded LANL's final requirement of 2400 cycles. Calculating the actual life from this good life data was a problem, because of just two failure points. As the testing proceeded LANL decided to halt many of the capacitors after 4000 shots. Maxwell's worst case Weibull analysis, assuming all 11 test units had failed, produced a 95% survival rate at ~3050 c/d cycles which fell between the two 1997 estimates. LANL's calculations were made based on nine data points and the results were accepted making Maxwell's Model No. 39232 the only qualified Atlas capacitor.

From the beginning, the design of Model No. 39232 was kept simple to facilitate high volume manufacturing. Minimizing difficulty improves quality and reliability when dealing with a 600 lb capacitor. Challenges were accepted and dealt with by Maxwell Energy Products' team throughout development and manufacturing, on the way to making Los Alamos National Laboratory's vision of a low inductance 60 kV, 650 kA, double ended fiberglass Marx capacitor a reality.

## VI. REFERENCES

*Articles from published conference proceedings:*

- [1] L. X. Schneider, S. R. Babcock, G. e. Laderach, "Lifetime Testing of Commercially Available 3.0 uF, 100 kV Pulsed-Power Capacitors," in *Proc. IEEE Pulse Power Conference '89*, 1989, p. 902.