

# TESTING OF HIGH ENERGY DENSITY CAPACITORS

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## *Abstract*

The U. S. Army Research Lab (ARL) is investigating the capabilities of high energy density capacitors at narrow pulse widths from two different manufacturers for high current pulsed power applications. Breakthroughs in this technology would allow smaller capacitor storage to be possible while retaining the same capabilities. The discharge pulse widths of the test shots were between thirteen and fourteen microseconds. These pulse widths were taken from the full wave half maximum pulse width (FWHM). Both capacitors are rated for 12.5 kJ of energy and are 250  $\mu$ F but have different volumes. The General Atomics Capacitors (GA-ESI 38982, 38994) have a total energy density of 1.3 J/cc while the manufacturer B's capacitor has an energy density of 0.64 J/cc. Both General Atomics' and manufacturer B's capacitors are polypropylene metallized film capacitors. While energy density is a major concern for our tests; attributes such as peak current, rise time, and high voltage lifetime were other factors to be considered. ARL is collaborating directly with General Atomics to help provide input and data in order to improve all properties of their capacitors.

## **I. Introduction**

The reason these capacitors are so important is because they can hold the same amount of energy while taking up less space and weight than previous models. The newest generation of capacitors is approximately 32 pounds per capacitor and less than ten inches tall. (Figure 1.) It was necessary to make sure that the only factors in the capacitors' degradation would be the total power and energy switched by the capacitor. For this reason we used purely resistive carbon washers for the load. The load was attached directly to the return case of the capacitor which minimized inductance in the test bed resulting in minimized reflections and current reversal. Taking this step should greatly extend the lifetime of each capacitor. The low inductance setup also allowed for a very fast current  $dI/dT$ . Prior to any

testing, the capacitor had its internal values checked with an LCR meter. An open and short circuit calibration on the LCR meter were performed to make sure that the values received would be accurate. At this point the ESR, Cs and Ls buttons are used to find the internal resistance, internal series capacitance and the internal series inductance by connecting the two terminals to the anode and the return of the capacitor. Once the test circuit has been built the total inductance of the system is found with a calibrated LCR meter. These values are then entered into Pspice for a more accurate simulation of the test circuit's peak current and load voltage waveforms. Next the capacitor was high potted to 10kv, for 5 minutes at a time. It was necessary to make sure that the capacitor is capable of handling high voltage for an extended amount of time. Secondly high potting a new capacitor allows the capacitor to go through self healing prior to high current being switched. The five minutes of high potting was chosen since in the field, charge time is approximately 20-30 seconds and then a shot is taken immediately for EM armor applications. Therefore 5 minutes of 10 kV would be well beyond what the capacitor needs to handle in real life conditions. This was done 4 times and the respective voltage drop over that amount of time was recorded. In the future other applications are being considered, therefore longer high pot and DC lifetime voltage tests need to occur. Afterwards the results of the four High pot tests were looked at to see if the capacitor is sensitive to high voltage being left on it for extended periods of time. Since the power supply did not have to use a noticeable amount of current (mA) to be applied in maintain 10 kV on the capacitor, the capacitor was ready for narrow pulse width, high current pulses.

## Report Documentation Page

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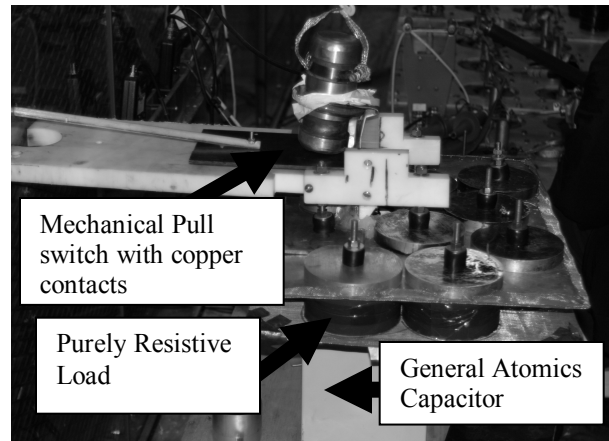




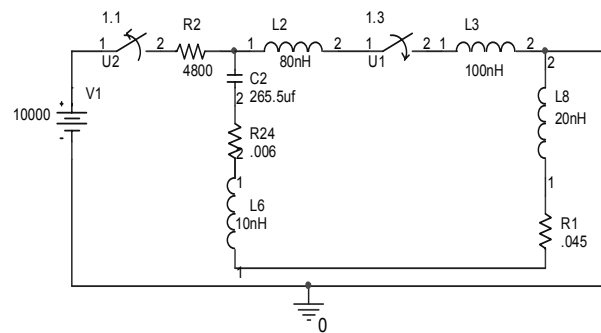
**Figure 1.** Picture of a single General Atomics capacitor from the newest generation GA-ESI 38994

## II. Evaluation

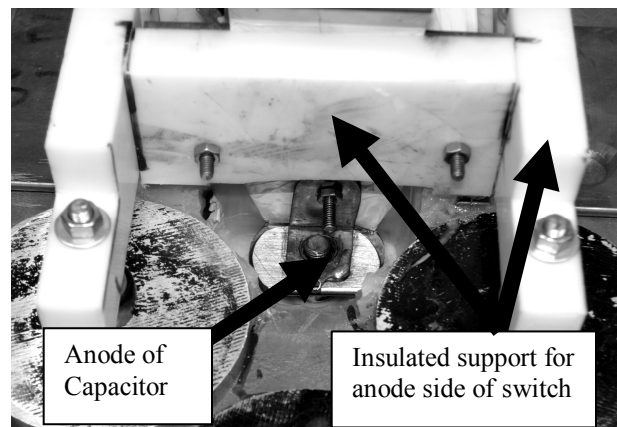
One hundred shots were taken on manufacturer B's capacitor as a reference for when we began testing on GA-ESI 38982. Over the 100 shots the capacitance and Q values dropped slightly. Manufacturer B's Q value actually rose at first. It is believed that this was due to a self healing process taking place in the early shots of the capacitor. From the peak Q value, till the one hundredth shot, the Q dropped from 610 to 530. The capacitance only dropped 0.2 uF, which was a 0.1% loss of capacitance. We expected to have similar results with capacitor GA-ESI 38994 however that was not the case. After 100 shots the capacitance and Q values had dropped significantly. It was decided that the capacitor should be taken to failure level (5% capacitance loss). This level of capacitance loss was achieved after 150 shots with each shot having an average peak current of 160 kA. The rise time of the capacitors reached upwards of 30 kA/us. The test setup chosen was a mechanical switch composed of three inch thick copper contacts on either side of an insulated pull switch mechanism. (Figure 2) Below figure 2 is a Pspice model of the ring down circuit used for testing the high density capacitor. (Figure 3) Although the copper contacts added a bit of extra inductance into the system, it was necessary to test the system with a durable switch. In case there were any failures or reflections in the circuit, only the capacitor would be damaged and not the switch. The total inductance of the test setup was ~200 nH. The connection to the anode of the capacitor was especially tricky because the anode contact area was small. We needed to create something small enough to fit into the area without causing arcing issues but still be sturdy enough to handle the weight of the copper contacts. (Figure 4)



**Figure 2.** ARL test bed with purely resistive load and mechanical pull switch.



**Figure 3.** Pspice model of the General Atomics ring down circuit



**Figure 4.** Close up of the anode connection to the mechanical copper contact switch.

## III. Results

The basic summary of capacitance and Q loss over the 150 shots has been put into table format for both the General Atomics and Manufacturer B's capacitor. (Figure 5.) After the failure in GA-ESI 38982 capacitor, this capacitor was sent back to General Atomics so that an autopsy could be performed to find

the nature of the failure. According to General Atomics there was no sign of any gas buildup associated with a typical failure mode in the capacitor so the next step was to inspect the interior of the capacitor. General Atomics discovered that “dissecting the winding assemblies revealed the capacitance loss was a result of the high peak discharge current damaging the end spray connection to the electrode”. Although the capacitor had been taken to technical failure, it is the belief of General Atomics that this type of failure would not result in a catastrophic failure [1]. Instead the capacitor would continue to lose capacitance at a quicker than normal rate. Unfortunately we were unable to prove this theory due to the capacitor being taken apart. If a failure of this variety occurred in the future, it would be beneficial to take the capacitor to a state of an even greater rate of loss of capacitance. A new experiment would need to be created to safely test this theory. This test would help to further characterize the capacitors behavior. General Atomics had two recommended improvements upon this generation of capacitor to improve electrode extension control. One way is to improve electrode extension control and the other is by adding a heat seal outside wrapper that will reduce the defect on the outside turn [1]. Improvements on the GA-ESI 38982 capacitor were made and currently the next generation of capacitors, the GA-ESI 38994 have arrived at ARL for further testing in high peak current pulsed power applications. Below are three figures that show the comparison between the two capacitors. The three graphs show the current waveform, voltage across the load and voltage droop respectively. (Figures 6-8)

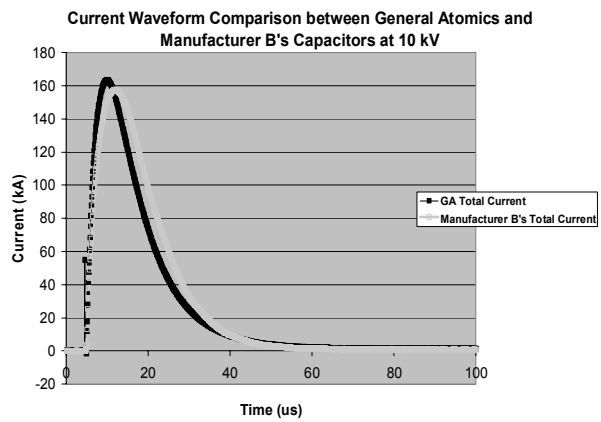
**General Atomics Capacitor**

Shots	Q	Capacitance (μF)	Percentage Drop
0	380	243.8	0%
50	244	241.9	0.80%
100	179	236.6	3%
150	220.7	230	5.70%

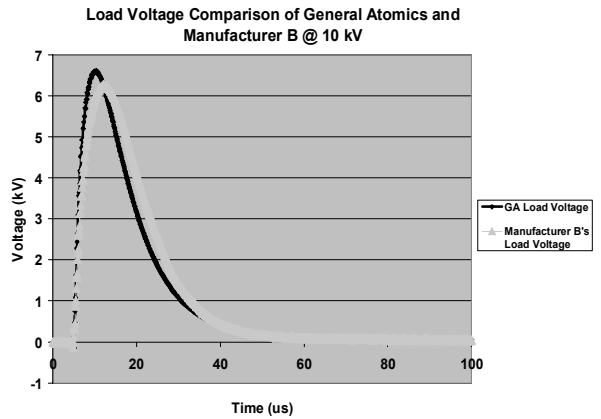
**Manufacturer B's Capacitor**

Shots	Q	Capacitance (μF)	Percentage Drop
0	475	265.7	0
50	610	265.6	0.01%
100	530	265.5	0.01%

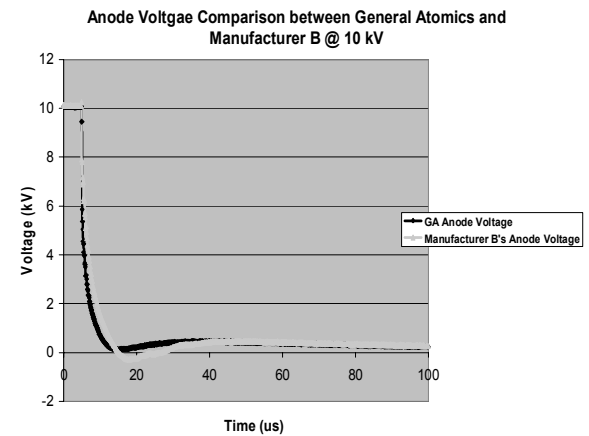
**Figure 5.** Table info for both the General Atomics and Manufacturer B's capacitor testing.



**Figure 6.** Current waveform comparison of the General Atomics and Manufacturer B's capacitor testing



**Figure 7.** Load voltage waveform comparison of the General Atomics and Manufacturer B's capacitor testing



**Figure 8.** Voltage Drop waveform comparison of the General Atomics and Manufacturer B's capacitor testing

#### IV. Conclusion

All future tests will be conducted on the GA-ESI 38982. One future test will be replacing the mechanical switch with a thyristor switch. Although the longer buss bars would add inductance into the overall system the test would better reflect what occurs in real life applications. Prior to the new switch being used a clamping diode would have to be installed in order to protect the thyristor switch from negative ringing. Five GA-ESI 38994 capacitors have also been assembled into a small Pulse Forming Network (PFN) setup that will test how these capacitors work with one another as well as how much current reversal negatively affects the capacitors. The five capacitors are interconnected to produce a pulse of 200 kA with a pulse width of 100  $\mu$ s. The highest current any given capacitor will see is 130 kA with a maximum current reversal of 20-30%. (Figure 8) This test will be conducted in the same manner as with the mechanical pull switch of the previous generation. This means that every 50 shots the capacitors values will be checked for changes in capacitance, Q, ESR and ESL. Another test that is being considered is a DC voltage lifetime setup at higher temperatures. No switching would occur in this situation. Ten thousand volts would be left on the anode of the capacitor around the clock. The anode of the capacitor would be monitored to see how much current from the power supply is needed in order to keep 10 kV on the anode at all times. This testing will not require capacitor discharging, but will require monitoring the high voltage power supply current that is needed to maintain 10 kV at capacitor terminals at all times. At the end of every week all values of the capacitor would be checked and recorded. All capacitors will be tested until a 5% capacitance loss is reached. All future capacitors that fail will also be returned to General Atomics so that an autopsy can be performed and improvements can be continued to be made. This sequence of events is done so that each generation can be improved upon. New capacitors of the GA-ESI 38994 have arrived at ARL and are being fitted into test beds. General Atomics believes that the GA-ESI 38994 capacitors will have improved attributes across the board including a longer DC lifetime.



**Figure 8.** PFN setup involving five capacitors that create a peak current of 200 kA for 100  $\mu$ s.

#### V. References

- [1]. Fred MacDougall and Chip Yang, General Atomics, Business PowerPoint presentation.