*GENERAL ATOMICS ENERGY PRODUCTS*
*Engineering Bulletin*

# RECENT DEVELOPMENTS IN PULSE POWER CAPACITORS

**J.B. Ennis, F. W. MacDougall, R.A. Cooper, J. Bates, N. Ozkan**

**Presented at:**

**2nd International Symposium on Pulsed Power and Plasma Applications**
**Korea Electrotechnology Research Institute**
**Chang-Won, Kyung-Nam, Korea**

**October, 2001**



GENERAL ATOMICS
Energy Products
SORRENTO ELECTRONICS
4949 GREENCRAIG LN, SAN DIEGO, CA 92123-1506
858.522.8400
www.ga-esi.com

# Recent Developments in Pulse Power Capacitors

J.B. Ennis, F. W. MacDougall, R.A. Cooper, J. Bates, N. Ozkan

*General Atomics Energy Products*
*Sorrento Electronics, Inc.*
*4949 Greencraig Lane*
*San Diego, California USA 92123-1675*
*www.hvpower.com*

***Abstract:*** High voltage, film dielectric capacitors are used in many pulse power circuits for energy storage, pulse generation, and pulse shaping. Capacitors are frequently a limiting factor for pulse power engineers in terms of size, cost, and parasitic impedances. Lifetime and reliability of capacitors, especially in systems containing large numbers of units, is always an important consideration.

General Atomics Energy Products (GAEP, formerly known as Maxwell Energy Products) offers several product types of high voltage capacitors for pulse power and dc filter applications, ranging from 200 Joule defibrillator capacitors to 100,000 Joule energy storage units used in large banks. Several styles of packaging are combined with a variety of dielectric/electrode systems to provide custom solutions. Examples of recent pulse power capacitors are described.

**Keywords**: capacitors, self-healing, high energy, energy density, energy storage

## 1. Introduction

Capacitors have been custom designed for many pulse power applications, ranging from heart defibrillators to national physics research facilities. In terms of capacitor design, each application has a different optimum solution. A wide variety of technologies is available to produce capacitors for different pulse power applications. This paper will briefly describe some of the applications and the capacitor designs that have been employed by GAEP.

## 2. Defibrillator Capacitors

Cardiac defibrillators are portable instruments that produce pulse waveforms specifically intended to polarize heart muscle tissue and end uncoordinated fibrillation of the heart, returning the heart to its normal pumping action. The electrical pulse originates with the discharge of a capacitor. Three basic types of waveforms are used in the United States: the Edmark waveform, a truncated exponential waveform, and a biphasic waveform. From a pulse power standpoint, the peak currents and power levels achieved in these applications are low, and the repetition rate and is also quite low. This allows very high energy densities to be achieved in capacitors designed for this application, as shown in Table 1.

**Table 1. Examples of GAEP External Cardiac Defibrillator Capacitors**

| Type | Edmark | Biphasic | Biphasic | Biphasic |
|---|---|---|---|---|
| MODEL | 30922 | 30920 | 30915 | 30932 |
| Capacitance, uF | 35 | 196 | 115 | 100 |
| Voltage, kV | 5.2 | 2.2 | 2.5 | 2.2 |
| Energy, kJ | 0.473 | 0.474 | 0.359 | 0.242 |
| Peak Current, Amps | 100 | 300 | 100 | 100 |
| RMS Current, A | 5 | 5 | 5 | 5 |
| Voltage Reversal, % | <10 | <10 | <10 | <10 |
| Life, cycles | 1.0E+04 | 1.0E+04 | 5.0E+03 | 1.0E+04 |
| Dimensions, mm | 49 x 74 x 146 | 49 x 74 x 129 | 49 x 74 x 86 | 48 dia x 129 |
| Volume, cc | 450 | 396 | 264 | 230 |
| Weight, kg | 0.49 | 0.43 | 0.28 | 0.25 |
| Energy Density, J/cc | 1.09 | 1.20 | 1.36 | 1.05 |
| Energy Density, J/g | 0.96 | 1.09 | 1.30 | 0.97 |

## 3. Self-Healing Energy Discharge Capacitors

Large energy storage capacitors are now commonly supplied with self-healing metallized electrodes. Examples are shown in Table 2. Both metallized Kraft paper with film and metallized film dielectrics are used, depending upon peak current, voltage, voltage reversal, ringing frequency, repetition rate, and other requirements. In metallized film designs, the metallized electrode may be “segmented”, divided into regions that are linked by fuses, so as to overcome limitations in the self-healing behavior of thermoplastic films. Metallized paper does not require segmentation, as it has excellent chemistry for self-healing, neither carbonizing nor melting when the metallization vaporizes around a breakdown site.

Typically, self-healing capacitors for pulse power have been limited to millisecond discharges from 30 kV or less, with peak currents less than 100 kA. However, some progress has been made in extending this technology to higher voltage applications, shorter discharge times, and higher peak currents. For example, GAEP has supplied self-healing capacitors rated as high as 60 kV for experimental applications.

The limitations on discharge time and peak current of metallized electrode capacitors are related. Given that there is a fixed current density limitation in the end spray termination of the metallized electrode, measured in Amps/cm of the winding length, the peak current rating of a given winding depends primarily on the width of the electrode. Higher current densities are achieved at a given capacitance and voltage by making longer windings of relatively narrow width material. The

Amp/cm rating may also be improved by using metallized paper rather than metallized film; by using cylindrical, rather than flattened windings; or by using other proprietary techniques.

**Table 2. Examples of GAEP Self-Healing Energy Storage Capacitors**

| | TYPE CM | TYPE CMF | TYPE CMF | TYPE CH |
|---|---|---|---|---|
| MODEL | 32765 | 32871 | 32781 | 32526 |
| Capacitance, uF | 309 | 38,000 | 90.3 | 100 |
| Voltage, kV | 24 | 1.5 | 30 | 20 |
| Energy, kJ | 83.5 | 42.8 | 40.6 | 20 |
| Peak Current, kA | 30 | 75 | 10 | 30 |
| RMS Current, A | 25 | 75 | 66 | 90 |
| Voltage Reversal, % | <15 | <10 | 10 | 10 |
| Life, cycles | >5.0E+04 | 1.5E+07 | 4.4E+04 | >2.0E+04 |
| Dimensions,mm | 343 x 406 x 914 | 343 x 406 x 699 | 298 x 425 x 635 | 305 x 356 x 394 |
| Volume, m3 | 0.127 | 0.097 | 0.080 | 0.043 |
| Weight, kg | 180 | 107 | 92 | 72 |
| | | | | |
| Energy Density, J/cc | 0.66 | 0.44 | 0.49 | 0.47 |
| Energy Density, J/g | 0.46 | 0.40 | 0.44 | 0.28 |
| COMMENTS | | LONG LIFE | LOW ESR | HIGH Irms |
| APPLICATION | FLASHLAMP DRIVER FOR HIGH POWER LASER | EM AIRCRAFT ARRESTOR | FLASHLAMP DRIVER | TUNNELING, ROCK-BLASTING |

As in non-self-healing, foil electrode capacitors, multiple series capacitances can be designed into individual windings by appropriate patterning of the metallization on each layer, providing for higher voltage capability. This allows the winding of wider webs of film or paper for greater production speed. However, the energy density achieved using this approach is limited by the risk of run-away capacitance loss in one or more of the internal sections, which can eventually result in a catastrophic failure.

Repetition rate and RMS current of metallized electrode capacitors is also limited, in this case by the poor thermal conductivity of the metallized electrode, as well as its significant contribution to Equivalent Series Resistance (ESR). Segmented metallized polypropylene is often the preferred approach for higher average power applications, because it allows for thicker metallization and thus, reduced ESR. This factor also tends to drive the design toward the use of narrower material and longer windings. GAEP's Type DM capacitors are general-purpose pulse discharge capacitors supplied in drawn metal cans that employ this technology. Such capacitors are used in a wide variety of industrial and research applications. Large energy discharge capacitors have also been built by GAEP using the same basic materials.

Another approach is to use both-sides-metallized paper or film as one electrode, effectively halving the resistance of the electrode. This technique reduces the energy density, however, as the thickness of the substrate layer of paper or film is not used for energy storage, and does not contribute to electrical or thermal conductance.

Another approach, utilized in GAEP's Type CH capacitors, is to combine metallized electrodes with foil electrodes so as to achieve self-healing in higher peak current and/or higher RMS current designs. These "hybrid electrode" capacitors are especially useful in long-life industrial applications, such as rock-blasting, water and food sterilization, etc.

## 4. Non Self-Healing Energy Discharge Capacitors

When the highest peak currents and voltages are needed, or where very high repetition rates and RMS currents are required , extended foil designs are still the most economical approach. In this area, recent development has focused on reducing Equivalent Series Inductance (ESL), reducing ESR, and improving life and reliability. Table 3 shows recent examples of this class of capacitor.

For fast Marx generator applications, GAEP has been supplying Type "FASTCAP" -- large insulating case capacitors with rail terminals, since 1986. Capacitors with rated voltages of 60 to 180 kV have been built, in some instances, two capacitors are enclosed in one case to minimize the inductance between them. The rail terminals have been designed to mate directly to low inductance railgap switches. The dielectric is high density Kraft paper, and multi-section extended foil windings are used. Application of these fast Marx generators is typically in large physics research facilities, where megavolt, megamp pulses are used to generate plasmas and X-ray radiation. Further development of this technology for future radiation effects experiments is currently underway.

Large metal cased capacitors with low profile bushings are generally more economical than large insulating cases, and are widely used in capacitor banks and Marx generators. For voltages >30 kV or repetition rate applications, extended foil designs with Kraft paper or mixed paper/film dielectrics are generally used. GAEP Type CS capacitors with "Scyllac" bushings are used for the highest voltage ratings (up to 100 kV) and highest peak currents in this class of capacitor.

Large metal cased capacitors with low profile bushings are generally more economical than large insulating cases, and are widely used in capacitor banks and Marx generators. For voltages >30 kV or repetition rate applications, extended foil designs with Kraft paper or mixed paper/film dielectrics are generally used. GAEP Type CS capacitors with "Scyllac" bushings are used for the highest voltage ratings (up to 100 kV) and highest peak currents in this class of capacitor.

**Table 3. Examples of GAEP High Peak Power Energy Storage Capacitors**

| | TYPE FASTCAP | TYPE CS | TYPE CS | TYPE CS |
|---|---|---|---|---|
| MODEL | 39232 | 32891 | 32899 | 32897 |
| Capacitance, uF | 33.5 | 17.5 | 11.1 | 2.6 |
| Voltage, kV | 60 | 40 | 36 | 100 |
| Energy, kJ | 60.3 | 14.0 | 7.2 | 13.0 |
| Peak Current, kA | 450 | 500 | 150 | 170 |
| RMS Current, A | 50 | 160 | 255 | 50 |
| Voltage Reversal, % | 15 | 60 | 60 | 35 |
| Life, cycles | 3.0E+03 | 1.1E+04 | 1.0E+06 | 1.0E+04 |
| Dimensions,mm | 330 x 737 x 711 | 305 x 406 x 724 | 305 x 406 x 673 | 279 x 356 x 635 |
| Volume, m3 | 0.173 | 0.090 | 0.083 | 0.063 |
| Weight, kg | 273 | 162 | 134 | 107 |
| Energy Density, J/cc | 0.35 | 0.16 | 0.087 | 0.21 |
| Energy Density, J/g | 0.22 | 0.086 | 0.054 | 0.12 |
| ESL, nH | 20 | <40 | <30 | <30 |
| COMMENTS | HIGH PEAK CURRENT, LOW ESL | HIGH PEAK CURRENT | REP RATE | |
| APPLICATION | PLASMA PHYSICS RESEARCH | ELECTRIC PROPULSION RESEARCH | PLASMA PHYSICS RESEARCH | PLASMA PHYSICS RESEARCH |

For repetition rate applications, mixed paper/film or all-film dielectrics are combined with extended foil construction to yield low ESR, low thermal impedance capacitors. Often the limiting factor for RMS current in such designs is the high voltage feedthru terminal. Mixed paper/film dielectrics are used where there is significant voltage reversal. All-polypropylene dielectrics, while having very low dissipation factor, are not resistant to damage from partial discharges that occur along the foil edges during high dV/dt transients.

## 5. Other Types of Capacitors

Other styles of capacitors frequently used in pulse power applications include a variety of plastic-case capacitors. Both extended foil and tabbed foil constructions are used to achieve different goals.

One example is the use of tabbed foil designs for very low inductance at high voltage, such as in GAEP Type S and SS single-ended plastic-case styles. These popular capacitors are used in small

Marx generators for laboratory use, medical lithotripsy, and many other fast pulse applications. These capacitors have relatively high ESR, however, due to (1) the contact resistance of the inserted tab connectors and the aluminum foil electrodes within the windings, (2) the use of multiple series tab connections to achieve typical ratings of 50 – 100 kV, and (3) a relatively lossy paper/polyester dielectric system. To reduce the ESR for high repetition rate applications, GAEP uses extended foil designs with low loss paper/polypropylene or all-polypropylene dielectrics in its Type SE/SSE capacitors. Such capacitors have been utilized in high power, high rep rate lasers.

Tabbed foil designs are also used in megavolt-rated "peaking" or pulse-shaping capacitors and in similar constructions used under high frequency AC or moderate repetition rate pulse applications at over 100 kV. These capacitors are plastic-cased with axial terminals, and the voltage is graded capacitively from one terminal to the other.

Axial terminal ("double-ended") plastic case capacitors, such as GAEP's standard PD/PM series, are the workhorse of repetitively pulsed systems in the 10-100 kV range. The design of these capacitors employs extended foil construction, mixed paper-polypropylene or all-polypropylene dielectrics, and standard materials, allowing rapid tailoring for specific ratings. Further reduction in ESL and ESR has been achieved for some recent specialty applications by using multiple feedthru terminals or rail terminals at each end.

## 6. Future Developments

The original "Maxwell" product, referred to as the Type M capacitor was a cylindrical welded steel case capacitor with low profile ceramic bushing originally developed for spacecraft electric propulsion. A special development effort in the late 1990's produced a new dielectric system which extended the life of this type of capacitor. Future space probes that require precisely adjustable impulses of thrust for positioning and attitude control may utilize these capacitors to drive pulsed plasma thrusters. In the meantime, the new dielectric system is being considered for use in more general purpose capacitors as a means of replacing paper/polypropylene and paper/polyester designs.

Another new dielectric system has been developed by GAEP for self-healing capacitors of high energy density at voltages in the 1 to 3 kV range. An example is Model 36459, 55000 uF at 1.2 kV, developed for an electromagnetic aircraft launch system. This new dielectric system is now being considered for other applications, such as defibrillators, which also require high energy density.

## 7. Conclusions

There are a wide variety of pulse discharge applications for capacitors. Most high volume applications use designs tailored to specific requirements for optimum performance at minimum cost. General Atomics Energy Products has available a wide variety of capacitor technologies to meet pulse power industry requirements.