GENERAL ATOMICS ENERGY PRODUCTS
Engineering Bulletin

HIGH ENERGY CAPACITORS OVERVIEW

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GENERAL ATOMICS
Energy Products
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HIGH ENERGY CAPACITORS

INTRODUCTION

General Atomics Energy Products (GAEP) designs and manufactures large energy storage / pulse discharge capacitors using a variety of dielectric and electrode systems that are optimized for different applications. Formerly known as Maxwell Energy Products, GAEP has a large manufacturing capacity for such capacitors and has delivered over 500 MJ since 1966. Examples demonstrating GAEP manufacturing capability are shown in Table 1. Such large capacitors are usually custom-designed for each application, but GAEP does maintain an inventory of standard materials that can be utilized for rapid prototyping. This document will review the available technologies used by GAEP and the applications for which they are most appropriate.

TYPE C – EXTENDED FOIL

Type C capacitors are large capacitors in fabricated, welded steel cases. Typical Type C capacitor cases range from 7-1/4 x 14 x 25 inches to 12 x 16 x 28-1/2 inches. A variety of high voltage terminals, current returns, and mounting schemes are available.

Figure 1. Type C capacitors, illustrating standard low profile bushing configurations.

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Table 1. Examples of High Energy Capacitors

HIGH ENERGY CAPACITOR MANUFACTURING EXPERIENCE									
Procuring Agency	Year Delivered	TYPE	Model	uF	kV	Capacitor Energy (kJ)	Number of Units	System	Total Energy (MJ)
(commercial OEM customer)	2001-2002	C	32899	11.1	36	7.2	30	Rep-rate plasma generator	0.2
(contractors for UC/LLNL)	2001	C	36372	65	28	25.5	32	NIF PILC	0.8
LOS ALAMOS NL	2001	CT	39276	2.3	100	11.5	6	LANSCE DC Filter	0.1
SLAC	2001	C	32892	8	30	3.6	40	DC Filter	0.1
Titan PSI	2001	C	32865	2.4	100	12.0	35	Lightning Simulator	0.4
TRW	2001	C	32864	2.1	100	10.5	25		0.3
Government Works/Redstone Arsenal	2001	C	32389	8.4	60	15.1	50	Lightning Simulator	0.8
General Atomics/USN	2001-2003	CMF	36447	46000	1.2	33.1	200	EM Aircraft Launch System	6.6
(commercial OEM customer)	2000-2002	CMF	36428	1350	1.5	1.5	100	Laser	0.2
NASA MSFC	2001	C	32891	17.5	40	14.0	100	Propulsion Experiment	1.4
General Atomics/USN	2000	CMF	32871	38000	2	76.0	50	Advanced Linear Motor	3.8
Sumitomo Electric Industries (Japan)	2000	CM	32851	333	22	80.6	6	Electrical Blasting	0.5
UC / LLNL	1999-2004	CM	32765	299	24	86.1	1200	NIF	103.3
LOS ALAMOS NL	1999	FC	39232	34	60	61.2	440	ATLAS	26.9
KOREA ELECTRIC RESEARCH INSTITUTE	1999	CM	32820	207	22	50.1	69	ETC Gun	3.5
NSWC	1999	CM	32823	279	22	67.5	20	n.a.	1.4
GEC ALSTHOM / TPC	1999	FM	36706	820	3	3.7	1098	AMTRAK NEC	4.1
GEC ALSTHOM / TPC	1999	FM	36707	1600	2.3	4.2	624	AMTRAK NEC	2.6
GEC ALSTHOM / TPC	1999	FM	36708	412	2.3	1.1	78	AMTRAK NEC	0.3
UC / LLNL	1998	CM	32765	299	24	86.1	17	NIF QUALIFICATION	1.5
FZ ROSSENDORF	1998	CM	32776	1667	10	83.4	15	High Field Magnetics Laboratory	1.3
MAXWELL SYSTEMS	1998	CM	32775	1085	9.6	50.0	5	Electroblast	0.2
Univ. of Rochester	1994	CM	36293	460	8	14.7	240	OMEGA LASER - ROD AMPLIFIER	3.5
Univ. of Rochester	1993	CH	36216	210	15	20.0	1764	OMEGA LASER	35.0
Los Alamos NL	1993	C	32567	24	50	30.0	164	PEGASUS Upgrade	5.0
Physics International/ARDEC	1992	C	32547	830	11	50.0	653	Kirkudbright EML Test Bed	33.0
Defense Nuclear Agency	1992	FC	39156	1.2	+/- 90	20.0	220	ACE 4	4.0
ARDEC/Picatinny Arsenal	1991	CM	32511	175	24	50.0	1040	Picatinny Arsenal	52.0
Vitronics/Ft. Monmouth	1991	CM	32511	175	24	50.0	130	Mobile PFN	7.0
Korean Electrical Research Inst.	1991	CT	32535	6.4	56	10.1	269	Circuit Breaker Current Injector	3.0
FMC	1989	C	32349	207	22	50.0	210	EML	11.0
Rheinmetall GmbH	1989	C	32283	52	44	50.0	130	CHECMATE replica EML	7.0
GTE/Hill AFB	1987	C	32382	37	42	25.0	45	1 MJ SREMP pulser with crowbar & Hill AFB	1.0
Defense Nuclear Agency	1986	C	32349	207	22	50.0	1426	THUNDERBOLT EML	71.0
Defense Nuclear Agency	1986	C	32369	830	11	50.0	700	Green Farm SSG EML	35.0
Defense Nuclear Agency	1984	C	32283	52	44	50.0	150	CHECMATE EML	8.0
Lawrence Livermore NL	1982	C	33677	52	22	12.5	600	NOVA	8.0
Defense Nuclear Agency	1982	C	32212	31.3	40	25.0	185	SREMP	5.0
Air Force Weapons Lab	1980	C	32184	6	60	11.0	1000	SHIVA II	11.0

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GAEP's Type C Extended Foil capacitors offer the highest peak currents of any type of capacitor, up to one million Amps for a single unit. GAEP's low profile bushings and internal construction techniques result in low inductance (30-200 nH), and low Equivalent Series Resistance (ESR). Coaxial current return rings are available for each style of bushing when the lowest inductance is required for fast discharge applications.

Paper Dielectric

The original Type C capacitors have a paper dielectric and extended foil electrodes. They are impregnated with castor oil, an environmentally friendly vegetable oil. These capacitors are suitable for "single-shot" and low repetition rate applications requiring high voltages (up to 100 kV), high peak current (up to 1 MA), high voltage reversal (>20%), or some combination of these factors. Energy densities up to 0.66 J/cc are available for lifetimes of a few thousand charge/discharge cycles using special high density Kraft paper. Type C paper dielectric capacitors have been the workhorse of large high energy physics and electromagnetic gun research facilities in the United States, United Kingdom, and Germany.

Mixed Dielectric

Mixed dielectric versions of Type C capacitors are available, using either polyester or polypropylene film in combination with paper in the dielectric. The electrodes are extended foil, and different liquid impregnants are used depending on the application. These designs offer lower ESR than all-paper designs for higher repetition rate applications, and higher insulation resistance for dc filter applications. This type of capacitor is usually designed for higher cycle lifetime applications that still require a robust, fault-tolerant design. For short lifetimes of a few thousand cycles, they have lower energy density than paper dielectric capacitors. Applications include industrial e-beam systems, accelerators, and dc power supplies.

All-film

All-polypropylene film versions of Type C capacitors can be utilized when maximum repetition rate and RMS current or minimum ESR is required. These capacitors are more sensitive to voltage reversal, ringing frequency, and temperature than paper capacitors, and are also less robust than mixed dielectric designs.

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TYPE CT - TABBED FOIL

In some cases, the extended foil construction may not be the most economical. A good example is a DC filter application, in which the capacitor need not provide high peak pulse currents. In such cases, GAEP can utilize flag tabs, inserted during the winding process, as the electrode terminations. GAEP's tabbed designs are usually built with mixed dielectric or all-paper constructions.

TYPE CM and CMF – METALLIZED ELECTRODES

Large energy storage capacitors used in millisecond discharge applications such as electromagnetic launchers, flashlamp drivers for inertial confinement fusion, and rock blasting are now commonly supplied with self-healing metallized electrodes. Examples are shown in Table 2. Both metallized Kraft paper with film (TYPE CM) and metallized film dielectrics (TYPE CMF) are used, depending upon peak current, voltage, voltage reversal, ringing frequency, repetition rate, and other requirements. Such capacitors have been used in large energy storage banks for research facilities in electromagnetic launchers and inertial confinement fusion, and smaller systems for industrial applications such as rock blasting, lasers, sterilization, and so on.

In TYPE CMF metallized film designs, the metallized electrode may be "segmented", i.e. divided into regions that are connected by fusible links, 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, 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.

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 the 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.

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

	TYPE CM	TYPE CM	TYPE CM
MODEL	32765	32820	32513
Capacitance, uF	309	206	175
Voltage, kV	24	22	24
Energy, kJ	83.5	50	50
Peak Current, kA	30	30	25
RMS Current, A	25	25	25
Voltage Reversal, %	<15	<20	<20
Life, cycles	>5.0E+04	2.0E+03	5.0+03
Dimensions,mm	343 x 406 x 914	305 x 406 x 483	305 x 457 x 387
Volume, m3	0.127	0.060	0.054
Weight, kg	180	82	78
Energy Density, J/cc	0.66	0.83	0.93
Energy Density, J/g	0.46	0.61	0.64

	TYPE CMF	TYPE CMF	TYPE CMF	TYPE CMF
MODEL	32906	32871	32781	36428
Capacitance, uF	2,000	38,000	90.3	6 x 225
Voltage, kV	5.0	1.5	30	1.5
Energy, kJ	25.0	42.8	40.6	1.5
Peak Current, kA	20	75	10	4.0
RMS Current, A	60	75	66	25
Voltage Reversal, %	<10	<10	10	20
Life, cycles	6.9E+04	1.5E+07	4.4E+04	2.0E+08
Dimensions,mm	203 x 279 x 425	343 x 406 x 699	298 x 425 x 635	203 x 229 x 194
Volume, m3	0.024	0.097	0.080	0.0090
Weight, kg	26.6	107	92	9.9
Energy Density, J/cc	1.04	0.44	0.49	0.17
Energy Density, J/g	0.94	0.40	0.44	0.15

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.

TYPE CH – HYBRID ELECTRODES

Industrial applications generally require a continuous train of repetitive current pulses, resulting in high RMS currents and long cycle lifetimes. High reliability is paramount, but compact size and low cost are also important.

GAEP's Type CH capacitors 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. Examples are shown in Table 3.

Type CH capacitors can be operated at higher peak currents than Type CM and CMF designs because extended foils are used for the terminations. This eliminates the weakest link in the metallized electrode designs, the end spray connection to the metallization. The current density is still limited by the metallized electrode, but this limitation is at a much higher current density level than the end spray connection.

The RMS current capability of Type CH capacitors is much closer to that of extended foil designs than to pure metallized electrode designs because the aluminum foils conduct heat out of the windings very effectively. This permits Type CH capacitors to be run at much higher pulse repetition rates than equivalent size metallized electrode capacitors.

COST COMPARISON

Figure 2 compares the relative cost (on a per Joule basis) of some of the different Type C technologies as a function of lifetime. Note that the selection of the proper capacitor technology depends on more than capacitor cost.

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Table 3. Examples of GAEP Type CH Self-Healing Energy Storage Capacitors

	TYPE CH	TYPE CH	TYPE CH	TYPE CH
MODEL	32526	36292	36172	36216
Capacitance, uF	100	100	20	210
Voltage, kV	20	6	17	15
Energy, kJ	20	2.0	2.9	23.6
Peak Current, kA	30	15	5	80
RMS Current, A	90	100	60	38
Voltage Reversal, %	10	20	20	20
Life, cycles	>2.0E+04	> 1.6E+10	>1.4E+05	>1.5E+05
Dimensions,mm	305 x 356 x 394	203 x 356 x 508	102 x 203 x 315	200 x 400 x 719
Volume, m3	0.043	0.037	0.0040	0.058
Weight, kg	72	58	11.7	92
Energy Density, J/cc	0.47	0.054	0.44	0.41
Energy Density, J/g	0.28	0.034	0.25	0.26
COMMENTS	High Irms, High Reliability	High Reliability, Long Life	High Reliability	High Ipk, High Reliability, Low Cost
APPLICATION	TUNNELING, ROCK-BLASTING	FOOD PROCESSING	LASER R&D	ICF EXPERIMENT

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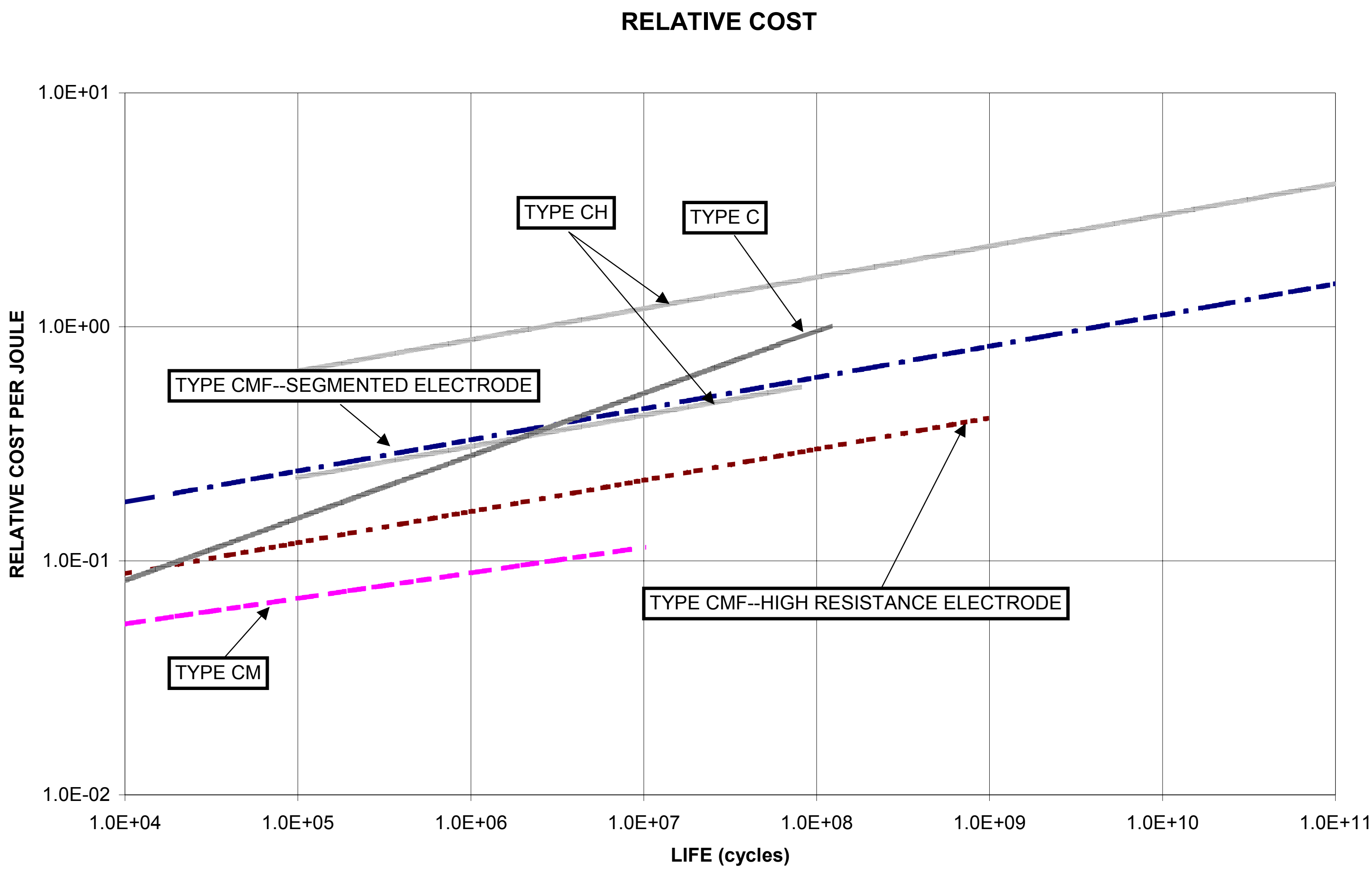

Figure 2. Relative Cost Per Joule versus Life of different high energy capacitor technologies.

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OTHER TYPES OF HIGH ENERGY CAPACITORS

For fast Marx generator applications, GAEP has been supplying Type "FASTCAP" -- large capacitors with an insulating case (e.g. fiberglass) 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.

Figure 3. FASTCAP Model 39232 capacitors being prepared for shipment to Los Alamos.

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A NOTE ABOUT SAFETY

Capacitors, especially high energy capacitors, can store lethal amounts of electrical charge at lethal voltages for extended periods of time. Discharge and connect together ("short out") the terminals of capacitors before handling. Do not work around high energy capacitors while they are charged. Be aware of potential explosion and fire hazards and take appropriate precautions.

RELATED PRODUCTS

GAEP also designs and manufactures power supplies, fuses, and resistors for use in high energy capacitor banks. Standard capacitor charging power supplies are available with output voltages up to 65 kV and average power up to 12 kJ/s. GAEP power supplies have been used for charging large single-shot capacitor banks at Los Alamos and Livermore National Laboratories, as well as for high repetition-rate applications. Fuses and resistors from GAEP are specifically designed for capacitor bank applications, and have low inductance and high peak power ratings.

Together with our affiliate company, General Atomics, GAEP/SEI also designs and assembles high power systems that typically integrate power supplies, capacitors, switches, and controls. Such systems are custom-designed for each application and range from individual rack-mounted chassis to multiple module stand-alone capacitor banks.

For more information on any of our products, visit our website, ***www.hvpower.com***, or contact our Sales Department, at 858-522-8400.

SUMMARY

GAEP has a well-established technology base for designing custom high energy capacitors for any application. GAEP's manufacturing capacity is one of the largest in the world for custom, high energy capacitors. Our demonstrated experience in installed capacitor banks is quite large and provides assurance of our technology, capacity, quality, and cost competitiveness.