A brief history of supercapacitors

It took 150 years for a concept established in the 1800s to become a technical reality, and a further two decades to make it commercially available. John Miller explains how today's electrochemical capacitors evolved from humble beginnings.

An electrochemical capacitor (EC), often called a Supercapacitor or Ultracapacitor, stores electrical charge in the electric double layer at a surface-electrolyte interface, primarily in high-surface-area carbon. Because of the high surface area and the thinness of the double layer, these devices can have very a high specific and volumetric capacitance. This enables them to combine a previously unattainable capacitance density with an essentially unlimited charge/discharge cycle life. The operational voltage per cell, limited only by the breakdown potential of the electrolyte, is usually <1 or <3 volts per cell for aqueous or organic electrolytes respectively.

> *"The unique attributes of ECs often complement the weaknesses of other power sources like batteries and fuel cells."*

The concept of storing electrical energy in the electric double layer that is formed at the interface between an electrolyte and a solid has been known since the late 1800s. The first electrical device using double-layer charge storage was reported in 1957 by H.I. Becker of General Electric (U.S. Patent 2,800,616). Unfortunately, Becker's device was impractical in that, similarly to a flooded battery, both electrodes needed to be immersed in a container of electrolyte, and the device was never commercialised.

Becker did, however, appreciate the large capacitance values subsequently achieved by Robert A. Rightmire, a chemist at the Standard Oil Company of Ohio (SOHIO), to whom can be attributed the invention of the device in the format now commonly used. His patent (U.S. 3,288,641), filed in 1962 and awarded in late November 1966, and a follow-on patent (U.S. Patent 3,536,963) by fellow SOHIO researcher Donald L. Boos in 1970, form the basis for the many hundreds of subsequent patents and journal articles covering all aspects of EC technology.

This technology has grown into an industry with sales worth several hundred million dollars per year. It is an industry that is poised today for rapid growth in the near term with the expansion of power quality needs and emerging transportation applications.

Following the commercial introduction of NEC's SuperCapacitor in 1978, under licence from SOHIO, ECs have evolved through several generations of designs. Initially they were used as back-up power devices for volatile clock chips and complementary metal-oxide-semiconductor (CMOS) computer memories. But many other applications have emerged over the past 30 years, including portable wireless communication, enhanced power quality for distributed power generation systems, industrial actuator power sources, and high-efficiency energy storage for electric vehicles

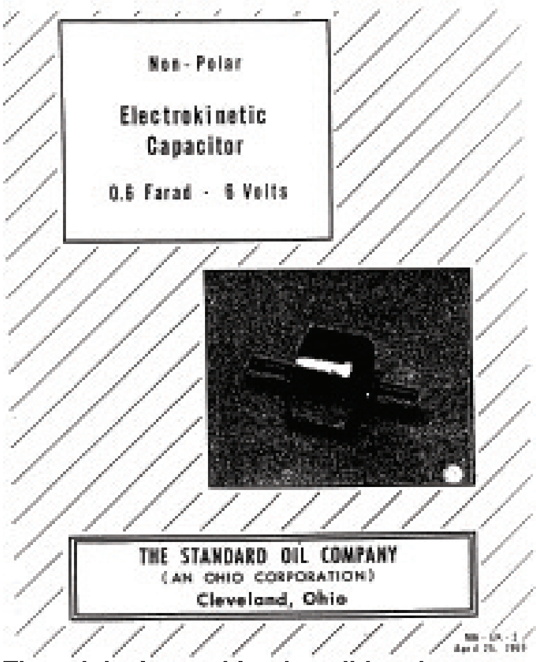
(EVs) and hybrid electric vehicles (HEVs). Overall, the unique attributes of ECs often complement the weaknesses of other power sources like batteries and fuel cells.

Early ECs were generally rated at a few volts and had capacitance values measured from fractions of farads up to several farads. The trend today is for cells ranging in size from small millifarad-size devices with exceptional pulse power performance up to devices rated at hundreds of thousands of farads, with systems in some applications operating at up to 1,500 volts. The technology is seeing increasingly broad use, replacing batteries in some cases and in others complementing their performance.

This article presents historical information about the development of EC technology and the applications this technology is used in. Information sources include technical publications, news releases, product brochures and personal communications. Information will not be provided for every EC ever developed, given that some developers were or are very small with only niche-market products, or have only recently entered the market.

1962: ELECTROCHEMICAL CAPACITORS AT SOHIO

Carbon double-layer capacitors originated with practical devices developed by SOHIO. Work began in the early 1960s as an outgrowth of fuel cell-related development activity. A fairly complete account of this early work was presented by Don Boos, one of the SOHIO chemists involved in the project, at a conference in 1991 called 'An International Seminar on Double Layer Capacitors and Similar Energy Storage Devices'.

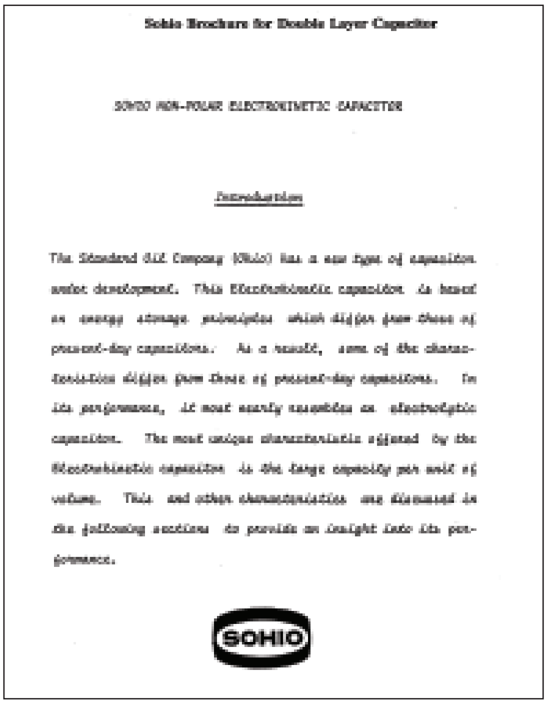


The original pamphlet describing the super capacitor concept.

In this presentation Boos described the discovery of the phenomenon and the early activity in developing practical devices. One account described the difficulty in obtaining stable electrical readings on fuel cells that often took a good part of a morning to reach steady-state operation. The length of time was attributed to charge actually being stored in the device. This led to the concept of using a pair of high-surface-area carbon electrodes to create an energy storage device. The product was referred to at the time as an 'Electrokinetic capacitor', and SOHIO provided samples of commercial prototypes to many parts of the market.

Figure 1 shows the cover of a brochure of 25 April 1969 used for marketing and sampling the Electrokinetic capacitor. The introductory page is shown in Figure 2.

Work at SOHIO was eventually geared towards developing a replacement for aluminium electrolytic capacitors. This was before the time that 'keep alive' memory back-up applications existed, i.e. it was long before CMOS memory or digital clock chips. Power rectification filtering was identified as the market, and considerable effort went into trying to develop or optimise the product for this application. It is interesting that some developers still have this as a goal today,



Sohio Brochure for Double Layer Capacitor

SOHIO NON-POLAR ELECTROKINETIC CAPACITOR

Introduction

The Standard Oil Company (Ohio) has a new type of capacitor under development. This Electrokinetic capacitor is based on energy storage principles which differ from those of present-day capacitors. As a result, some of the characteristics differ from those of present-day capacitors. In its performance, it most nearly resembles an electrolytic capacitor. The most unique characteristic offered by the Electrokinetic capacitor is the large capacity per unit of volume. This and other characteristics are discussed in the following sections to provide an insight into its performance.

SOHIO

Figure 3: NEC – Tokin capacitors.

some 30 years later – a goal still not satisfactorily met using double-layer charge storage technology.

Because SOHIO was heavily in debt from building the Alaska pipeline, in 1971 it made cuts in many long-term development programmes, including the capacitor project. They had not yet, however, licensed the technology. The first licensee failed to commercialise the technology and the licence reverted back to SOHIO.

The second licensee was Nippon Electric Company (NEC) of Japan. Starting in 1975 NEC carried out fundamental investigations, rapidly developed manufacturing capability, and began to market the 'Supercapacitor' in 1978. It is for this reason that the only appropriate use of the term Supercapacitor is for NEC's EC products. These were aimed primarily at the emerging CMOS memory back-up application and at clock chip back-up, providing back-up power for these devices in VCRs, clock radios, microwave ovens and similar consumer electronic goods.

After oil began flowing through the Alaska pipeline in 1977 SOHIO resumed its capacitor development activities. The 'Maxcap' double-layer capacitor product was introduced in the early 1980s, having an aqueous electrolyte and bipolar construction, and rated up to several farads and 5.5 volts. With consolidation in the oil industry, ownership of the Maxcap product line shifted first to Carborundum, then to Cesiwid, and finally to Kanthal Globar.

1975: ELECTROCHEMICAL CAPACITORS AT NEC

NEC began its fundamental investigations in 1975 after licensing the technology from SOHIO. Having rapidly developed manufacturing capability, NEC began pre-production of the FA series in 1978. These were sampled for many different potential applications. Mass production followed in January 1980. In 1982 sales of EC products with different optimisations (i.e. new model series) began. Many other product models were introduced in the 1980s to meet new application requirements.

One unique feature of the NEC capacitor design was bipolar construction. NEC developed processes to stack six or eight cells in series in a bipolar arrangement and successfully seal the entire device. This is significant because this simple construction eliminates the need for cell interconnects. (The same approach has been subsequently used by several other companies, notably ECOND and ELIT, in their very large high-power capacitors.)

NEC reported development of much larger double-layer capacitors in 1991, using an activated carbon composite electrode. Because of their essentially rigid electrodes, these devices did not require high compression for good performance. In 1996 the product brand name was changed to Tokin. Several new products were introduced in the 1990s, including the FG series, the high power FT series, and the FC series. In 2001 a spiral-wound series and a low-profile thin-format series, both having organic electrolyte, appeared. The brand name was changed from Tokin to NEC-Tokin in 2002. Figure 3 shows some of the EC product series produced by NEC-Tokin.

NEC has certainly been one of the leaders in the technology over the past 30 years, with a rich history of developing and marketing EC products. Indeed, it is the only company that makes a true 'Supercapacitor'.

1975: ELECTROCHEMICAL CAPACITORS AT ECOND

In December 1993 Dr Alexander Ivanov presented a paper at the Third International Seminar on Double Layer Capacitors and Similar Energy Storage Devices that described ECs much larger in size than devices available in the U.S. or Japan. Dr Ivanov's company, ECOND, was located in Moscow and had ties with the Russian Ministry of Railroads. He described large capacitors being used to start 3,000 horsepower diesel locomotive engines. These capacitors not only stored a large amount of energy, but they were also some of the most powerful reported up to that time.

The ECOND 'PSCap', as the devices are called, uses a bipolar construction with an aque-

Figure 4: One of the first hybrid city transit buses using capacitor energy storage.

ous electrolyte. The design is a cylinder about nine inches in diameter and, depending on the stored energy, from several inches up to more than two feet in height. Energies range from a few kilojoules up to 45kJ for the PSCap used in locomotive engine starting. Equivalent series resistances of modules are typically in the milliohm range. Module voltages up to 200 volts are common. The RC-time-constant of the PSCap is a fraction of a second, considerably less than that of most previous products.

The 1993 Ivanov paper was an eye-opener for capacitor developers at the meeting, especially with the projected need at that time for a 1.8MJ load-levelling energy storage system for use in electric vehicles. The achievements reported were a significant step ahead of research reported in the U.S. and Japan, and provided significant encouragement for many capacitor developers in the West.

In a recent letter to me, Dr Ivanov related some of the obstacles he faced in his early capacitor research activity, which started in the mid 1970s. A 1974 Report of the USSR Academy of Sciences contained the paper 'Anomalous Electrical Capacity and Experimental Models of Hyperconductivity' describing a molecular capacitor. Much scepticism was expressed—both by the Academy and by the Government – about this type of storage technology, referred to as 'molecular energy storage'. Nevertheless development funds were granted, but with very close oversight. This work eventually led to the development in 1980 of a kV-rated, MJ-sized capacitor system, followed shortly by a 'Government State Premium' award to the researchers responsible for this achievement.

Beginning in 1985, development efforts focused on transportation applications related primarily to internal combustion engine starting. The ECOND Corporation was created in 1991 to commercialise the technology under Dr Ivanov's direction. Since 1994 ECOND capacitor products have been used in many U.S. demonstration systems, like diesel truck starting, as well as in HEVs. An article in the Spring 2007 issue of BEST describes several of these demonstrations. Figure 4 shows one of the first gas-electric hybrid city transit buses to use capacitor energy storage – 1.6MJ of 200 volt PSCap modules. These capacitors are also available through a Canadian distributor.

1978: ELECTROCHEMICAL CAPACITORS AT PANASONIC

Panasonic began manufacturing its 'Goldcap' double-layer capacitors in Japan in 1978. These were initially developed primarily to replace the unreliable coin cell batteries used in memory back-up applications at that time. The major differences between the Panasonic and NEC products were the electrolyte and the fact that NEC used an aqueous electrolyte in a 'pasted electrode' with bipolar cell construction, while Panasonic used a nonaqueous electrolyte in a non-pasted electrode in the cell construction. The nonaqueous electrolyte offered the advantage of higher unit cell operating voltage. The non-pasted electrode in the Goldcap allowed Panasonic to produce ECs without obtaining a licence from SOHIO.

Panasonic developed two distinct designs. One was a coin cell, used to replace battery-type coin cells; the second was a spiral-wound configuration, similar to that of an aluminium EC. The initial Panasonic product had a voltage rating of approximately 1.8 volts per cell, a considerable step up from the cell voltage of NEC products. This meant that for the 5.5 volt rating popular at

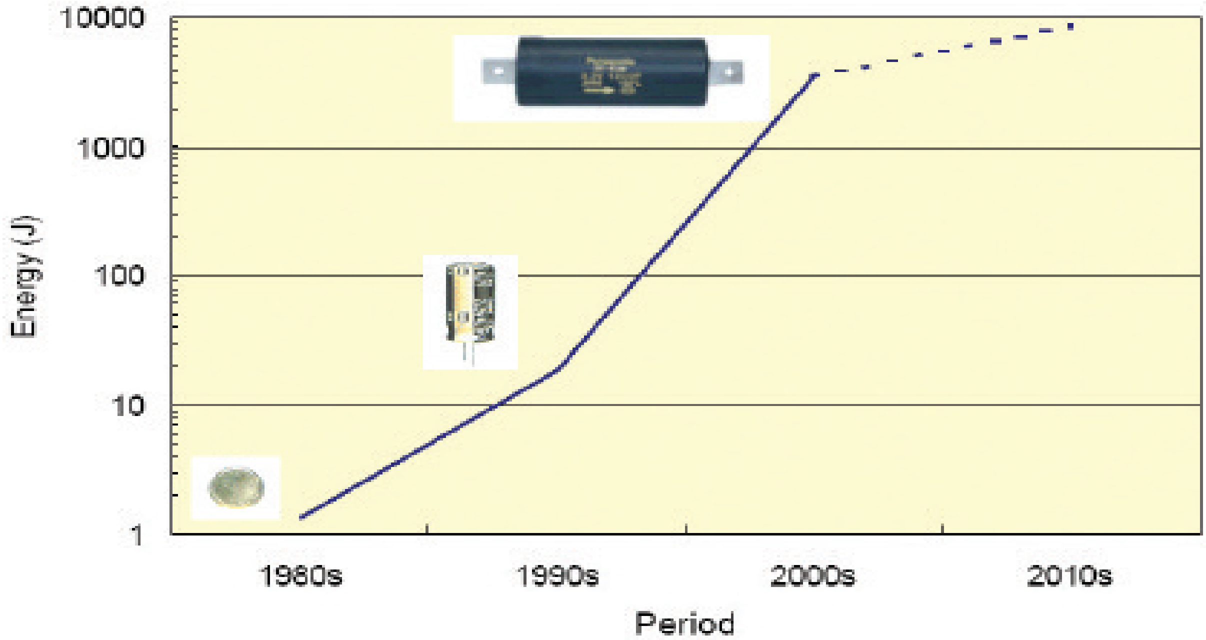


Figure 5: The performance improvements in Panasonic Goldcap capacitors.

the time of introduction only three series-connected cells would be required, rather than the six series-connected cells required using NEC's comparable Supercapacitor.

In the mid 1980s Panasonic manufactured button-cell capacitors in several different sizes: one-half farad, two-thirds farad, and so on. These became very popular for solar-powered wrist watches. The advantage of using a capacitor in that application was that it did not have the life limitations of a battery and could therefore be sealed into the watch during manufacturing, eliminating the need for a battery-replacement cover seal which might leak. The watch was generally charged from an amorphous silicon photovoltaic material located around the perimeter of the watch face. Charging took several minutes in direct sunlight or several hours in weak room light. The coin cell capacitor stored sufficient energy to operate the watch for 24 hours or longer (in darkness).

Panasonic began manufacturing much larger EC prototypes in the 1990s. These were spiral wound and rated at 470F, 2.3 volts or 1,500F, 2.3 volts. The former of these were extensively tested for possible use in load-levelling electric vehicles. Subsequent advances increased the energy in that same size product from 470F to 800F.

In 1999 Panasonic introduced the 'UpCap' capacitor, rated at 2,000F and 2.3 volts, for transportation applications including HEVs. The device is very well engineered, with a sophisticated double seal for preventing water entry into the package that is a much lower-cost arrangement than welded construction. It has essentially continuous tabbing of the spiral foils at each end, which helps reduce series resistance, as well as

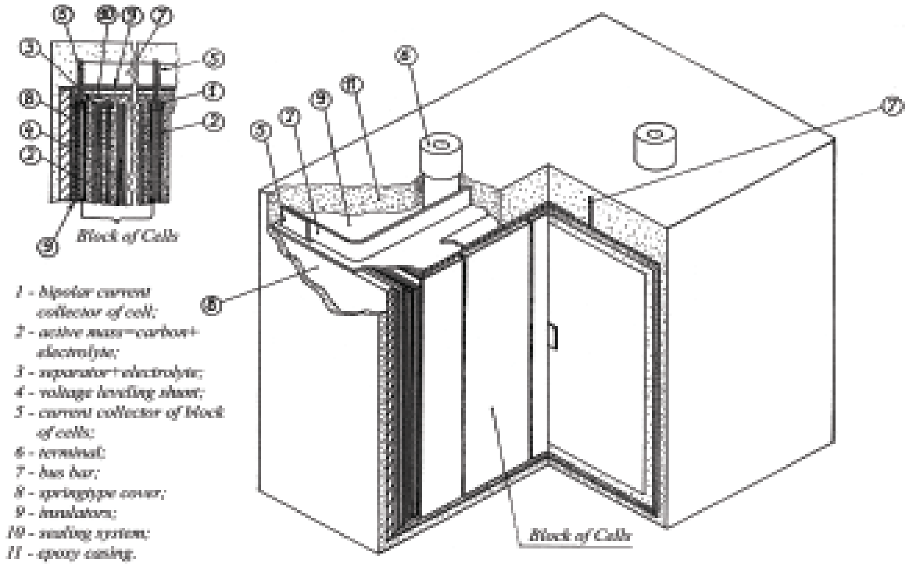


Figure 6: A cut-through of ELIT's first asymmetric EC.

helping to extract any internally generated heat. This is important for the repetitive charge/discharge cycles of hybrid vehicles, including regenerative braking in stopping and acceleration after the stop. Figure 5 shows the historic size trends of the Panasonic Goldcap EC cells.

1988: ELECTROCHEMICAL CAPACITORS AT ELIT

In early 1993 Alexey Beliakov, Technical Director for MP Pulsar in Kursk, Russia, sent a reader's letter to Batteries International. He wanted to correct information in an earlier issue by pointing out the existence of his company's large ECs. He presented pictures of very large capacitors, 30 and 50kJ, rated for 12 and 24 volts, used for engine starting. He described the testing done on these devices and talked about delivery of a 600kJ set of capacitors. Capacitors of this size and sophistication were totally unheard of in the U.S. at that time.

MP Pulsar changed its name to ELIT. Development of the ELIT capacitor began in 1988 at the Accumulator Plant in Kursk. A year later the developers had created the first asymmetric EC, one based on a nickel oxyhydroxide positive electrode, potassium hydroxide electrolyte, and an activated carbon negative electrode. These devices were designed to power wheelchairs and, subsequently, children's cars. ELIT's emphasis shifted in 1990 to symmetric designs with potassium hydroxide electrolyte and two activated carbon electrodes. Its capacitors use bipolar construction and a prismatic form factor, as shown in the cutaway in Figure 6.

Modules with voltages as high as 400 volts and capacitor sets of 1,500 volts can be produced, although nominal 12 and 24 volt modules for vehicle applications are more common. The ELIT capacitor is very powerful, having an RC-time-constant of a small fraction of a second. ELIT has developed an automated and flexible production line (Figure 7), currently with a production capability of more than 250,000kJ of capacitors per year. ELIT sells large numbers of ECs in Russia and has sold over 30,000 in the U.S.

1989: ELECTROCHEMICAL CAPACITORS AT ELNA

Elna, in collaboration with Asahi Glass of Japan, developed and began selling several styles of their organic electrolyte Dynacap EC in the U.S. starting in the late 1980s. Elna produces coin cells and spiral wound products, some with the same package size and ratings as the Panasonic Goldcap. They

Figure 7: ELIT's production line in Russia.

do, however, make several families of capacitor cells quite different from Panasonic's, in sizes up to 200F and rated at 2.5 volts. One of its product lines is very powerful, with RC-time-constants between 0.1 and 1 second, depending on size, and it has developed and commercialised an EC cell with a 3.0 volt rating.

At the Centennial Meeting of the Electrochemical Society in 2002 Asahi Glass's Dr T. Morimoto described an asymmetric EC with an intercalation electrode paired with a double-layer charge storage electrode, both electrodes being carbonaceous and using an organic electrolyte containing a lithium salt. The energy density of unpackaged prototypes was reported to be 16 Wh/l. Today several groups are advancing this and similar approaches, because of both the higher operating voltage (4.2 volts) offered and the resulting higher energy density provided – perhaps twice that of symmetric carbon-carbon ECs. Commercial production of capacitors with this asymmetric design is imminent.

1991: ELECTROCHEMICAL CAPACITORS AT MAXWELL

Before 1991 Maxwell Technologies of San Diego, California had developed a broad line of high-voltage capacitor products used in many of the early magnetic fusion machines and other high-energy-density applications of the time, like laser flash-lamp power supplies. In 1991 the company was awarded a contract by the U.S. Department of Energy (DoE) to develop advanced ECs, in response to a broad-area request by DoE in 1990 for EC development proposals.

The goal was a technology suitable for load

Figure 8: A Maxwell Boostcap.

levelling a battery storage system in EVs. It included a capacitor that would store 500 Wh (1.8MJ) of energy, be capable of delivering 50kW of power, operate at 300 volts, weigh less than 100kg, and have a specific energy greater than 5 Wh/kg. Additionally the materials costs for this energy storage system were to be less than $1,000. This initial DoE specification provided the basis for the Maxwell development programme, and it served likewise as a guide for many other developers of EV load-levelling capacitors.

Maxwell worked jointly with Auburn University in capacitor development. The technology that they initially chose was a metal-carbon fibre composite electrode with aqueous potassium hydroxide electrolyte. The metal fibres were initially nickel, sintered to carbon fibres. The idea was to reduce the electronic resistance that had been observed in some electrodes made with particulate forms of carbon and also to take advantage of the shape of a single fibre as opposed to more sphere-like carbon particles. Eventually Maxwell changed its design to an organic electrolyte and also changed the material from nickel-carbon to aluminium-carbon cloth, with the intention of improving specific performance. In the mid 1990s Maxwell's EC development efforts moved from the Auburn facility to San Diego.

In 2002 Maxwell purchased the EC manufacturer Montena Components of Rossens, Switzerland. Rapidly this led to several product changes that included replacing the accordion-folded, metallised carbon cloth electrode material previously used in the larger cells with carbon-coated aluminium foil current collectors which were then wound into cylindrical cells.

Maxwell has developed a broad family of EC products called BoostCaps. Cells range in size from a small hermetically packaged 5F cell, through the wound 350F D-cellí size to the very large 3,000F, 2.7 volt rated tubular cells having a series resistance of <0.3 mW (figure 8). Packaging for the larger-size components is well engineered using penetration-weld attachment techniques to electronically bond the spiral-wound current collectors to the package terminals and thus provide low series-resistance and very effective heat extraction. The larger devices are being used in many applications, including HEVs, distributed generation systems like wind turbines, and internal combustion engine starting modules.

Maxwell licensed its technology to EPCOS in Germany in the 1990s. (EPCOS elected to exit this market in late 2006, reportedly due to the anticipated length of time predicted before profitability was achieved.) In conclusion, Maxwell Technologies has grown into the leading U.S. producer of ECs clearly aimed for the world market.

1993: ELECTROCHEMICAL CAPACITORS AT ESMA

In December 1997 Dr Arkadiy Klementov delivered a presentation titled 'Application of Ultracapacitors as Traction Energy Sources' at the Seventh International Seminar on Double Layer Capacitor and Similar Energy Storage Devices. He showed photographs of buses and trucks powered solely by ECs: no batteries, no gas engines. Some in the audience missed the point that such heavy electric vehicles were powered solely by capacitors. This was the first disclosure in the West of capacitor systems of such large size and of capacitors with energy densities exceeding 10 Wh/kg. The capacitor bank used for propulsion in the trucks and buses could store about 30 MJ of energy at 190 volts. The invention that ESMA created to store energy for these traction applications was an asymmetric capacitor (U.S. patent 6,222,723 and earlier Russian patents). This design essentially uses one battery electrode mated with a double-layer charge storage (capacitor) electrode. The combination offers certain advantages over the standard, more common symmetric design. These include higher specific energy, higher operating voltage for an aqueous electrolyte, lower materials costs since the charge storage carbon effectively has twice the capacitance, and voltage self-balancing in high-voltage strings of capacitor cells. These four advantages are extremely important in many of today's applications.

The Joint Stock Company ESMA (of Troitsk, Russia) was created in 1993 for the development and manufacture of ECs. The systems that ESMA has developed range in size from small 20kJ, 14 volt modules up to very large 190 volt, 30MJ systems used to power buses and trucks. Cells range in size from 3,000F to more that 100,000F. Cell construction is similar to that used in aircraft NiCd batteries but with activated carbon substituted for cadmium in the negative electrode. The ESMA cells are flooded, have the ability to reach voltage balance naturally in series strings, and offer very good power performance with high cycle life.

The design offers very favourable cost advantages over organic electrolyte products, since material purity issues are not as important, materials and package drying is unnecessary, and hermetic (welded metal) packaging is not needed. However the nickel foil used for the current collectors has, like most metals in the recent past, become very expensive, negating some of these cost advantages.

ESMA has at least three capacitor optimisations: pulse capacitors, which are intended for discharges of a few seconds or less like engine starting; intermediate-power capacitors, like those needed in hybrid vehicles; and traction capacitors, designed to power electric vehicles like fork lifts, utility vehicles, trucks and buses. Generally these traction devices can be charged in 12 to 15 minutes and discharged during one or more hours of operation. Several U.S. demonstration projects using ESMA capacitors have been reported, including an uninterruptible power supply (UPS) that delivered 100kW for ten seconds.

ESMA and its business partner American Electric Power (AEP) have reported advances made in a significantly lower-cost lead oxide/sulphuric acid/activated carbon asymmetric EC at the recent 2007 Advanced Capacitor World Summit. They are developing this technology to store large amounts of electricity from the utility grid at night, when there is abundance, for use during the next day, when it may be in short supply. Night storage/day use like this would involve only a single cycle per day, some 365 cycles in a year – a small number indeed. A storage system designed to last for ten years would require no more than 5,000 cycles, a number readily achievable with asymmetric ECs but a real stretch for many battery systems.

The recent ESMA paper also reported good cycle efficiency, with an estimated cycle life greater than 5,000 cycles. The energy density is much higher than that of symmetric ECs, and it

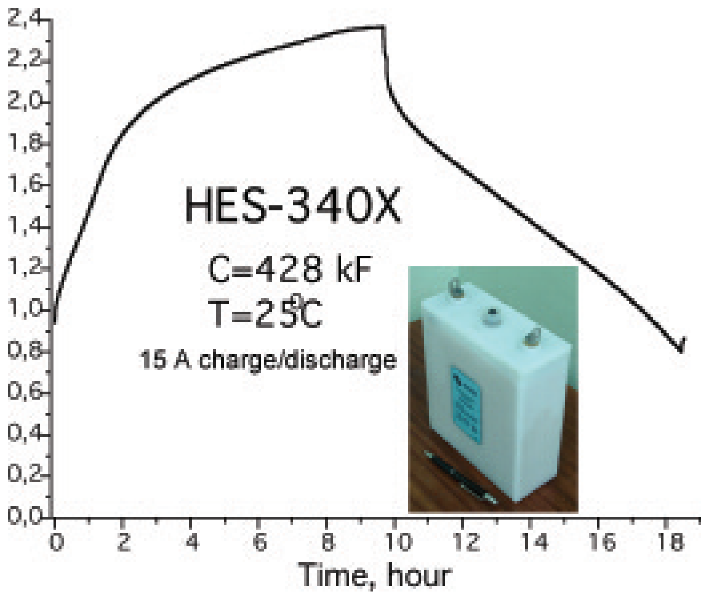


Figure 9: A charge/discharge curve for an ESMA supercap designed for electric utility use.

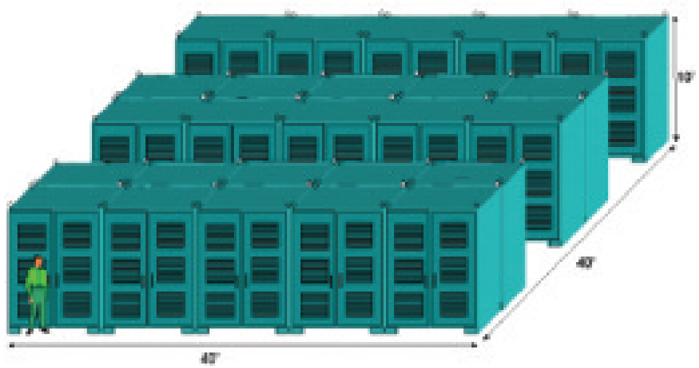


Figure 10: A concept drawing of capacitor-based energy storage system.

approaches, although it is still less than, that of lead-acid batteries. Figure 11 shows a photograph of one of these day/night storage capacitor prototypes that has been optimised for a charge/discharge cycle of five hours charging and five hours discharging. Figure 12 is a concept drawing that was presented by the DoE three years ago for a capacitor system that provides 1MW for five hours. Presently it is the economics of such systems that determine their viability, any questions about technological feasibility appearing already to have been answered.

1994: ELECTROCHEMICAL CAPACITORS AT CAP-XX

In 1994 Commonwealth Scientific & Industrial Research Organization (CSIRO) of Australia entered into a partnership with Plessey Ducon, a manufacturer of passive components, to evaluate

Figure: 11 Australian Cap XX device. One of the smallest and most power components on the market.

EC technology and its market potential. Two years later the development team produced a high-energy-density carbon and organic electrolyte capacitor capable of storing up to 9 Wh/kg, with time constants ranging from seconds to milliseconds. These devices used spiral-wound single cell construction.

In 1997 Cap-XX Pty Ltd was formed to develop small high-power devices for the mobile computing and wireless markets. It has built a commercial production facility and now manufactures a series of various small size, very high-power capacitors. These have a flat prismatic profile and employ minimal packaging, as shown in Figure 13. They are constructed without the use of welding or glass-to-metal seals. Typical products include pairs of series-connected cells rated at 4.5 volts, with capacitance in the range 0.12F to 0.8F. ESR on all these products is 0.1 ohm or less, and RC-time-constants are as short as 20ms. These small components are among the most powerful ECs on the market, intended for pulse-power portable electronics markets like digital wireless communication.

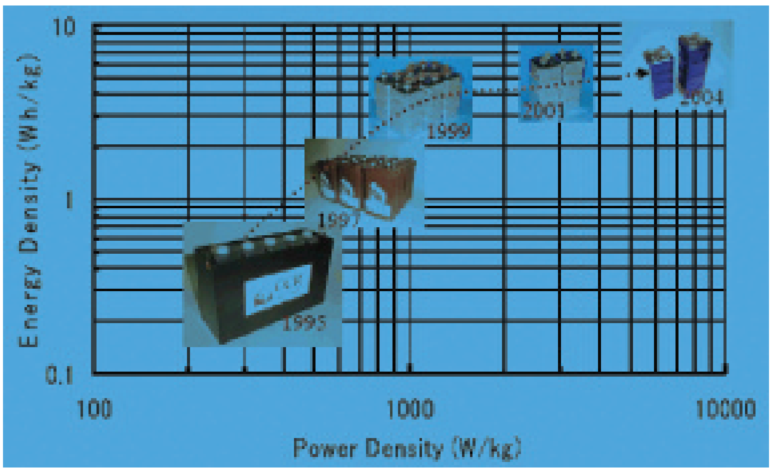


Figure 12: NCC supercaps showing an improving performance trend.

1995: ELECTROCHEMICAL CAPACITORS AT NIPPON CHEMI-CON

Nippon Chemi-Con (NCC) of Japan is a billion-dollar manufacturing company that has earned the distinction of having the largest slice of the world aluminium electrolytic capacitor market. So when NCC introduced its DLCAP EC product line in the U.S. at the 2005 Advanced Capacitor World Summit, uncertainty about the long-term viability of large EC components instantly evaporated. NCC described products that had been optimised for either energy or for power, and presented test data that strongly suggested NCC had considerable prior experience with this technology.

Indeed they had – more than ten years of EC research and development activity dating back to work with Isuzu Motors in 1995. The time-line shown in Figure 14 charts the advance of the technology. NCC prototype production began in 1997 and mass production in 1998, with both spiral wound and prismatic cells being made, the largest having a 3,000F, 2.5 volt rating.

The DLCAP is unique in several respects. First, it is built on the many years of related materials, packaging and manufacturing experience that NCC acquired from the aluminium electrolytic capacitor business it began in 1931. This degree of vertical integration is unmatched in the EC industry. Second, NCC uses a propylene carbonate solvent in its electrolyte that does not have the fire and health issues associated with some of the alternative organic electrolytes. And third, truly understanding the cost issues of mass production and recognising that practical limitations on material purity will lead ECs to generate some gas during operation that can lead to package swelling, NCC incorporated the innovative pressure-regulating valve in the DLCAP package (shown in Figure 15). The valve serves the purpose of releasing any generated gas that may build up to a low, yet specified, pressure – whether it arises from normal operation or from abuse conditions like the application of excessive voltage or over-temperature. Note that this resealable valve approach is only feasible with nontoxic electrolytes.

Most petroleum used in Japan is imported, making energy conservation very important to the country. Thus many of the present NCC EC applications relate to capturing, storing and re-using

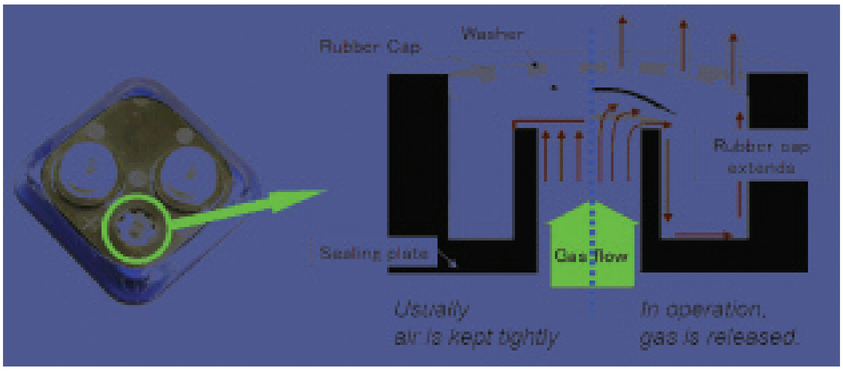


Figure 13: The DL Cap from Nippon Chemicon showing its release valve.

energy that normally would be wasted as heat. An example is seaport gantry cranes used to load and unload container ships (Figure 16): energy stored while lowering a container is subsequently re-used to assist in lifting the next one.

Figure 14: NessCap capacitor module rated at 5,000 farads.

Reported energy savings from using DLCAP energy storage is 40% over a conventional system. Similar levels of savings have been achieved with other industrial equipment having repetitive back-and-forth or up-and-down motion.

1998: ELECTROCHEMICAL CAPACITORS AT NESSCAP

The NessCap EC was initially created from technology spun off from the Daewoo Group of Korea. Starting up in 1998 with both public and private funding, NessCap rapidly developed capacitor manufacturing capability and a broad product line of ECs. NessCap products use an organic electrolyte with spiral wound prismatic cell construction. Its first commercial shipment of capacitors to the U.S. market was in mid 2000.

NessCap currently makes cells from a few farads to 5,000F in size, and some of them are rated at 2.7 volts, among the highest voltage in the industry. The larger capacitor cells have prismatic packages for efficient stacking in modules. NessCap recently introduced a product line of 42 volt modules for the automotive market. Applications for NessCap capacitors are broad and range from transportation to power quality. Figure 17 is a photograph of a 5,000F NessCap EC.

NessCap has also developed a complementary high-energy-density line of EC products based on pseudocapacitance charge storage. These devices have a single-cell design like the company's double-layer capacitor products, offer energy density advantages, but have lower cycle life. A popular application for these components is in solar-powered lighting as in light-emitting tiles, road studs and garden lights. In these electricity generated by solar cells is stored in the pseudocapacitor and used at night to power LEDs in the system.

SUMMARY

We can characterise the 30-year history of EC technology perhaps best as one of continual breakthrough development, in which initial cost challenges have consistently led to innovations that not only meet cost concerns but open up new avenues of discovery. Electrochemical capacitor technology still has many miles to go in terms of technical promise and practical applicability.