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In this introduction to the Special Issue on pulsed power and its applications, background information is provided for the non-specialist to better understand the many challenges in designing pulsed power systems, and the wide diversity of applications that are now emerging. The approach to providing a tutorial on pulsed power technology is to make available to the reader the paper written by J.C. Martin which appeared in a Special Section of the PROCEEDINGS OF THE IEEE on pulsed power technology in June 1992. That paper is supplemented in this introduction with additional information that complements many of the invited papers composing this Special Issue.

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Scanning the Technology

Modern Pulsed Power: Charlie Martin and Beyond

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In this introduction to the Special Issue on pulsed power and its applications, background information is provided for the nonspecialist to better understand the many challenges in designing pulsed power systems, and the wide diversity of applications that are now emerging. The approach to providing a tutorial on pulsed power technology is to make available to the reader the paper written by J. C. Martin which appeared in a Special Section of the PROCEEDINGS OF THE IEEE *on pulsed power technology in June 1992. That paper is supplemented in this introduction with additional information that complements many of the invited papers composing this Special Issue.*

Keywords**—***Bioelectrics, explosive pulsed power, high-power microwave, intense beams, plasma pinches, pulsed power, radiography, ultrawideband microwaves.*

I. INTRODUCTION

Modern pulsed power has its genesis in the pioneering work of the late John Christopher Martin and his colleagues at the Atomic Weapons Establishment, Aldermaston, U.K., in the 1960s [1]. "Charlie," as he was known to the community, was a hydrodynamicist who was frustrated by his inability to purchase an adequate X-ray radiography source to image the dynamic phenomena he was interested in. As a result, he pursued a new generation of radiography sources that were based on high-power Marx generators, coupled with low-impedance transmission lines, and cold cathode single-stage accelerating gaps. Thus was the birth of modern pulsed power.

Pulsed power science and technology rapidly disseminated to the United States, former Soviet Union and the present-day Russia, Europe, and Asia. Pulsed power refers to the technology whereby energy is accumulated over a relatively long period and then compressed in a short period to deliver very large power pulses to a given load. In this regard, pulsed power is an enabling technology; that is, its development has been spawned by some application (the "load") that requires a very large power pulse for a relatively short period. Typical loads historically have included charged particle beam diodes, imploding plasmas, and other primarily defense-related applications; today, however, the loads can be biological samples, water from municipal drinking supplies, or effluents from combustion processes, among other environmental and biomedical applications. In short, pulsed power has evolved to not only play an important role in defense, including homeland defense, but has evolved to become an important technology in the environmental and biomedical arenas as well.

One of the reasons that pulsed power has emerged to become an important technology in the defense and nondefense sectors alike is that compactness and portability have increasingly become attributes of pulsed power systems. This is attractive to the defense sector, since the move to "all-electric" vehicles (for the army, navy, and air force alike) motivates the need for electrically driven (directed energy) weaponry. In the nondefense arena, compact pulsed power systems are more attractive to any practical application.

For some applications, it is desirable (and necessary) to achieve reliable repetitive operation of pulsed power systems. Early examples of repetitive pulsed power systems employed thyratron switches [3], described in more detail below. Extension of single-shot technology to applications requiring 100 Hz or higher repetition rates requires extraordinary innovation in order to achieve systems with long lifetime and good reliability.

In order to better grasp the breadth of pulsed power activities, we are motivated by the "mouse-to-elephant" curve in biology, shown in Fig. 1. The fact that all mammals (on this log–log plot) fall about a fairly straight line whose slope is power per unit mass should not be surprising, since mammals are made from similar matter, consume carbon-based food supplies, and breathe oxygen. Fig. 2 presents a plot of peak output power as a function of size (volume) for a wide

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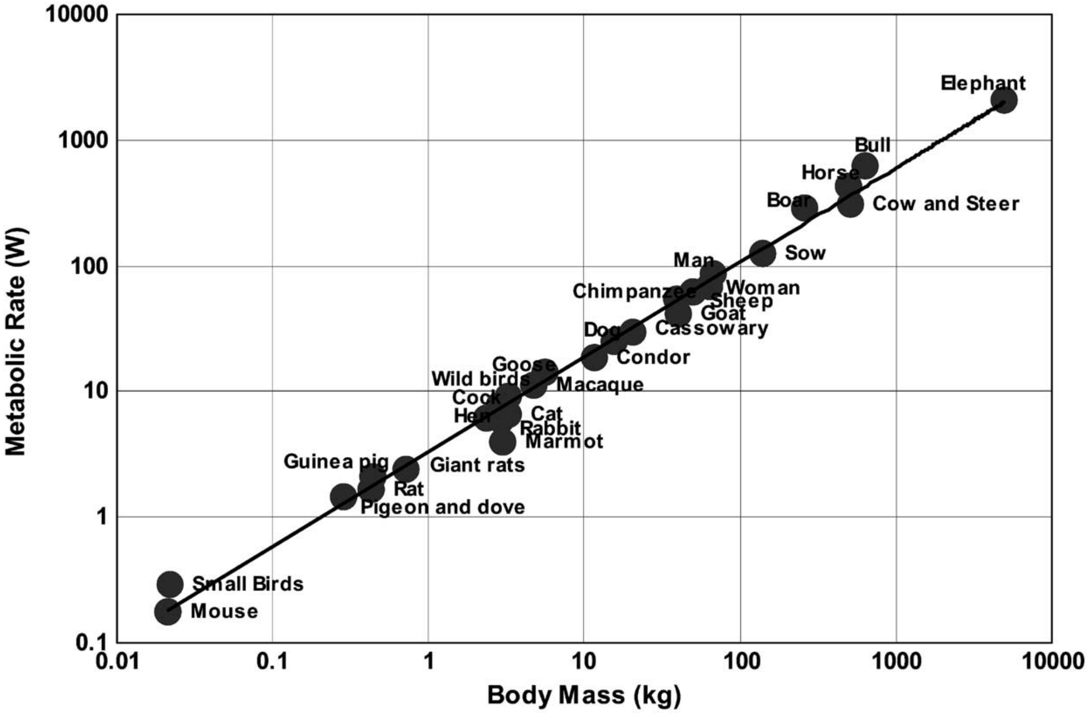

Fig. 1. The mouse-to-elephant curve in biology.

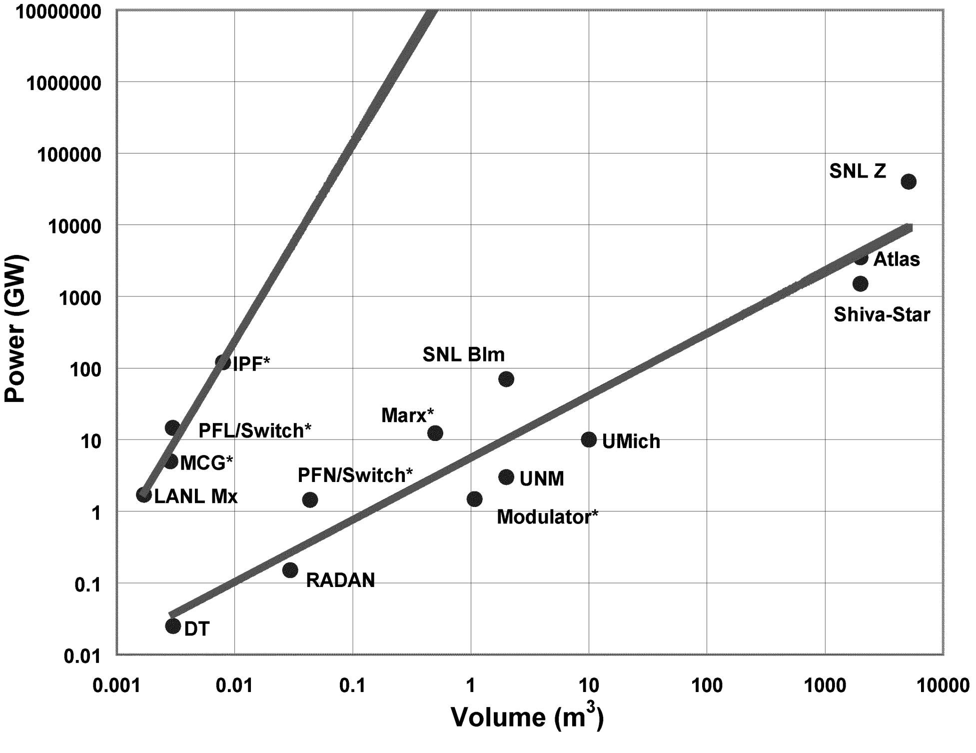

Fig. 2. The analogy of the mouse-to-elephant curve in pulsed power. The line with the faster rising slope comprises systems either driven by explosives or that use state-of-the-art high energy density components. The line with the lower slope represents more traditional pulsed power systems found in the laboratory. (Parameters for the sources denoted with an asterisk were obtained from [2].)

variety of pulsed power systems. This is an analogy of the mouse-to-elephant curve where the "mouse" is a compact hand-held pulsed power system developed at Los Alamos National Laboratory, Los Alamos, NM [4], and the "elephant" is the "Z" accelerator at Sandia National Laboratories, Albuquerque, NM, used for high energy density physics research [5], [6]. Since most pulsed power systems are made using similar materials, the power density uniting these sys-

Table 1
Summary of Typical Various Pulsed Power Requirements for Given Applications

Application	Electrical Energy	Pulse Length	Peak Power/Pulse	Burst Avg. Power
High Energy Density Plasma Physics	20 MJ	100 ns	>10's TW	N/A
Intense Electron Beam Radiography	200 kJ	70 ns	< 1 TW	N/A
High Power Microwave (Narrowband)	10 kJ	100 ns	100 GW	100 kW
High Power Microwave (Ultra-Wideband)	10 J	1 ns	10 GW	10 kW
Ion Beam Modification of Materials	< 10 kJ	100 ns	30 GW	Small
Bioelectrics	0.1 mJ – few J	10 – 100's ns	10 kW – 100 MW	< mW - few W

tems describes a straight line, the line with the lower slope in Fig. 2. The challenge of future pulsed power systems, in this regard, is to develop and incorporate novel materials that would then increase the power density of future pulsed power systems. The line with the faster rising slope illustrates such systems, ranging from inherently efficient explosively driven pulsed power systems to those manufactured using newer higher energy density components.

II. EXAMPLES OF PARAMETERS OF PULSED POWER SYSTEMS

The largest pulsed power systems are those used in the laboratory to study high energy density plasma physics and equations of state. They routinely generate in excess of tens of terawatts of electrical power. These include the Sandia National Laboratories' "Z" accelerator and its planned upgrades [5], [6], and the Los Alamos National Laboratory's Atlas machine [6] (which is now located at the Nevada test site). These large systems are intended to produce a single high-power pulse, and then would require some maintenance before being able to produce another pulse. The resultant shot rate on these large machines is typically about a single pulse per day.

Contrast this with high-power microwave sources, as another example, where some of their pulsed power accelerators can deliver 100-ns electrical pulses with tens of gigawatts of power and can be repetitively pulsed in burst mode with repetition rates as large as 1 kHz. These systems can operate for many shot cycles with minimal maintenance.

Table 1 summarizes the parameters of pulsed power systems used in some typical applications.

III. ADDITIONAL SUPPLEMENTARY INFORMATION

The 1992 paper by J. C. Martin [1] should be read first.[1] Additional technical information is provided here that is not covered in the Martin paper, but nevertheless would be valuable to better understand some of the papers appearing in this Special Issue.

A. Pulsed Power Switching

In this section, we review some basic features of pulsed power switches. It is convenient to distinguish between gas-phase and solid-state switches, partly because the applications in pulsed power to some extent, although not totally, divide accordingly. Some of the work in pulsed power engineering at this time is directed toward distinguishing which switch is most appropriate for a given application and in responding to and applying new developments in both types. At this time, although there are exceptions for certain applications, those applications requiring high hold-off voltage and high current with fast switching time tend to require gas-phase switches. Solid-state switches such as thyristors are also used, but because of limitations in turn-on time, and requirements for multiple switches for high hold-off voltage, are still somewhat restricted in terms of application.

1) Gas-Phase Switches: Gas-phase switches primarily include spark gaps, thyratrons, and the pseudospark switches. These have advantages including the gas, or plasma (ionized gas), is very forgiving to a one-time overcurrent or overvoltage. The switch will still work; its lifetime merely will have been reduced. This is in sharp contrast to solid-state switches, where just the one-time formation of an arc is catastrophic. The plasma allows transport of very high currents along with high hold-off voltage, and switching times can be very fast. The power dissipation in these switches is relatively low, attributed to the conductivity of the plasma that is formed in the gas. Plasma properties vary, however, and a distinction may be made between a spark gap, typically operated at high pressure ($\geq$1 atmosphere), in an "arc" mode, and a thryratron and/or pseudospark, which normally operate at pressures below 1 torr, and in a glow discharge mode.

Gas spark gaps: Gas spark gaps have been used under a very wide range of single-pulse (or few-pulse) conditions, and operate with varying lifetimes at very high voltages and currents with very fast switching times. The primary limitation is in lifetime and repeatability, this because the type of arc formation at high current tends to be erosive, thus altering electrode characteristics. Gases include N_2, air, H_2, SF_6, and

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[1] [Online] Available: http://www.ieee.org/organizations/pubs/proceedings

liquids such as water and liquid nitrogen. Voltages in excess of 1 MV and total charge >100 Coulombs have been obtained for important applications, such as Z-pinches for high energy density plasma physics research. Commercial spark gaps rated for 50–75 kA are available.

Triggering is achieved by techniques that include overvolting the main gap, introducing a plasma by auxiliary electrodes, or introducing UV through an overvolted auxiliary electrode. Radiation initiates breakdown through generation of charge by photoemission. Such optical triggering can be enhanced by using a laser. The closure time can be very fast: ≤ 5 ns. Most large pulsed power machines currently operating under single pulse mode utilize a spark gap switch.

Thyratrons: The original idea of a thyratron was conceived and patented by Langmuir [7], [8]. The general idea might be construed to include what is now known as an ignitron, which is a mercury cathode that conducts with a plasma of mercury vapor (and is capable of very high current operation). Development of a thyratron with high hold-off voltage was an enabling technology for repetitive pulsed power applications, such as radar modulators, and resulted from innovations by Germeshausen [9]. The thyratron for repetitive pulsed power applications (radar, pulsed lasers, and linear accelerators) is typically operated with H_2, or H_2 with D_2, although occasionally other gases are also used. Pressures are typically of the order 0.5 torr. The hold-off voltage can be very high, up to 100 kV for specialized tubes. Peak currents range to a few kA, much less than what commercial spark gaps are capable of handling; however, pulse-to-pulse repeatability is very good for millions of pulses. Thyratron lifetimes can be a billion shots in applications within specifications. The thyratron has the important advantage of a relatively low forward drop compared with vacuum tubes, due to space charge neutralization by the plasma in the tube, which can be critical for repetitive high peak power switching.

Pseudosparks and back-lighted thyratrons: The commercially less widespread pseudospark (electrically triggered) and back-lighted thyratron (BLT—optically triggered pseudospark) are similar to the thyratron in that the plasma is formed in a gas that is initially at pressures $\approx$0.1 to 0.5 torr. They differ in the operation of the cathode. For both the thyratron and the pseudospark, the limitation in current capability is found in the cathode, not in the plasma. Among the goals in developing the pseudospark was to achieve higher peak current, and this has been demonstrated.

The pseudospark cathode, or "superemissive" cathode, operates in a distinctly different mode from the externally heated thyratron oxide cathode. The superemissive cathode, which produces current from an area that is approximately 1 cm^2 of the order 10 000 A/cm^2, vastly in excess of conventional thermionic cathodes, achieves this through a two-step self-heating process. In the first step, a hollow cathode discharge is formed, leading to a self-heating (resulting from the field and plasma) of a thin cathode surface layer. This cathode layer reaches emission that is extraordinarily high through a combination of field emission and thermionic emission [10].

Table 2
Summary of Various Switch Parameters in Pulsed Power Applications

Switch (selected for pulsed power, approx. max)	Hold-off Voltage (kV)	Peak Current (kA)	Forward Drop (V)
Spark Gap	100	10 to >1000	20
Thyratron	30	1 - 10	150
Pseudospark	35	5 - 100	200
Thyristor	1-5	1 to 50	2
IGBT	1	1	3
MOSFET	1	0.1	V_{DS}
Vacuum Tube	200	0.25	Child-Langmuir

Pseudospark and BLT switches have been operated with hold off voltages in excess of 50 kV for a single gap, and 100 kV for two and three gaps. Peak currents for a typical switch are of the order 5–10 kA, although specialized versions conducting up to 200 kA have been reported. Switching times, that is, the time from approximately 10% to 90% of peak current, are of the order 25 ns in properly designed circuits, about a factor of two faster than a typical fast thyratron. Some versions of thyratrons apparently incorporate pseudospark emission characteristics in the design of concentric grid structures, leading to a combination of self-heated and externally heated cathode structures and operation. Pseudosparks are very robust to current reversal, and are reported to operate for switched charge lifetimes of the order 100 to 400 kC.

2) Solid-State Switches for Pulsed Power: Although unable to handle the parameters of large pulsed power systems, solid-state switches are nevertheless finding increasing applications in compact pulsed power systems. Principal solid-state pulsed power switches include the thyristor, gate-turn-off thyristor (GTO), insulated gate bipolar transistor (IGBT), and metal–oxide–semiconductor field-effect transistor (MOSFET). (See a recent Special Issue of the PROCEEDINGS OF THE IEEE for more detailed information on advances in power electronics [11].) These switches have the advantages that when operated within specifications will live very long and have reduced housekeeping requirements, but that when high voltage, high current, and fast rise rates are needed have some severe limitations not yet overcome for practical applications. Table 2 summarizes parameters of typical switches used in pulsed power applications.

a) Thyristors for pulsed power: Thyristors rely on triggering that results in an avalanche breakdown to form a solid-state plasma allowing high current conduction, and in this way are analogous to thyratrons (removing the gate voltage will not turn the device off). Thyristors, and

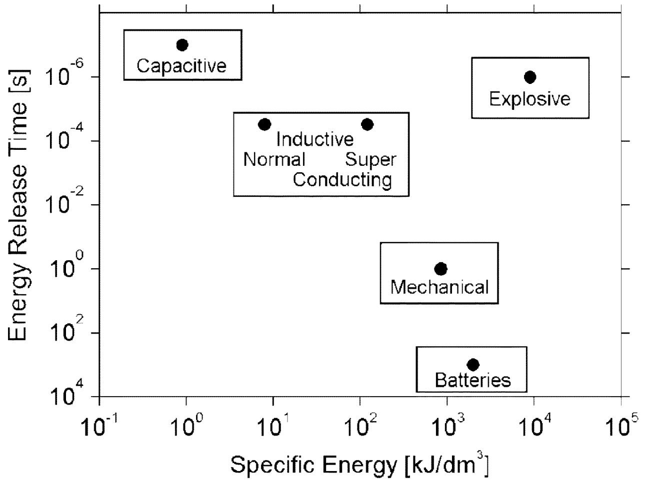


Fig. 3. Approximate specific energy and energy release time for diverse types of energy storage. (The explosive energy storage does not include the efficiency of transforming mechanical into electrical energy.)

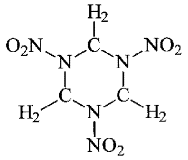
particularly GTOs, can hold off several kilovolts and switch hundreds of amperes. The rate of current rise is limited by the diffusion time in silicon, and failure mode is associated with the formation of a constricted arc accompanied by irreversible damage to the semiconductor. Although materials with higher mobility than silicon have been studied, other inherent material issues have thus far limited development for pulsed power. Applications for thyristors can be well correlated with pulse length—for example, major accelerator facilities requiring switching devices tend to use thyristors if the pulse lengths are many microseconds or longer, and thyratrons if the pulse lengths are a few microseconds or shorter.

b) Other gated solid-state switches: The MOSFET and IGBT are faster devices and turn off upon removal of the gate voltage, but have reduced current handling capability. Both are undergoing continued development and finding applications in systems where other switches have dominated. The IGBT, in particular, has been finding applications as a replacement module for thyratron switches.

Of interest are also new materials for various of these devices, such as SiC-based vertical MOSFET designs, which show promise for fast current rise and high hold-off voltage.

B. Explosively Driven Pulsed Power

Storage of energy and fast release is the prerequisite for any pulsed power system. Traditionally, capacitive and inductive storage have found most widespread use enabling extremely fast energy release, as indicated in Fig. 3. Mechanical energy storage systems have a higher specific energy (stored energy per volume or weight) but are slower in their energy release. Any reactive chemicals such as simple gasoline (when mixed with oxygen) have many orders of magnitude higher specific energy compared with capacitive, inductive, or mechanical energy storage. However, the comparatively slow reaction (maximum flame front velocity of a premixed H_2-O_2 flame is $\sim$10 m/s) of chemical fuels forbids their direct use in a pulsed power energy storage and release system. High explosives (HEs) that carry fuel and oxidizer within each molecule (see Fig. 4) are the only group of chemicals that provide reaction times in the microsecond regime. A typical HE, such as RDX, Cyclo-1,3,5-trimethylene-2,4,6-trinitamine, has a detonation speed in excess of 8 km/s or 8 mm/μs. Composition 4, C-4, with RDX as major constituent (91% by weight) is widely used for demolition, mining, and military applications. Other components of C-4 are mainly plasticizers, also including 1.6% motor oil (cf. Fig. 4). Its fast reaction time makes HE a prime candidate for the direct conversion of chemically stored energy into pulsed power.



Component	Percent (weight)
RDX	91.0
Di(2-ethylhexyl) sebacate	5.3
Polyisobutylene	2.1
20-weight motor oil	1.6

Fig. 4. Molecular structure of RDX and detailed C-4 composition.

The basic idea for efficiently transferring the chemical energy of the HE into electrical power is footed on the same principle that makes any standard electrical power generator work. A varying magnetic flux in an area enclosed by conductors induces a voltage in the conductors that will drive an electric current depending on the load connected to the generator. While the standard generator utilizes a rotating magnetic field to produce the needed flux variation, the typical explosive generator compresses the flux by explosively deforming conductors enclosing and trapping the initial magnetic flux. This conductor deformation occurs during several microseconds to several tens of microseconds, depending on the overall size of the generator. A simple estimate for the runtime of an explosive generator is its size divided by the detonation velocity of the HE used. For instance, a generator with 30-cm length will operate for about 40 μs if C-4 with $\sim$8 mm/μs is used. Other ideas for generating pulsed power explosively rely on shock-demagnetizing permanent magnets, "squeezing" ferroelectric or piezoelectric materials, and implosive flux compression utilizing semiconductive materials.

It should be noted in this context that the peak pressure produced by the detonation of C-4 is about 20–30 GPa. This pressure is several orders of magnitude greater than the tensile yield strength of any metal. As an example, aluminum 6061, which is often used in explosive generators, has a yield strength of 400 MPa. Hence, the metal will yield to the explosive pressure and deform easily on the microsecond time scale.

The benefits of explosive driven pulsed power are clear: roughly a factor of 10 larger specific energy than capacitors with similar discharge characteristics, possible stand-alone systems without requirement for power supply and other prime power, and long shelf life. Hence, explosive pulsed power has been receiving considerable interest for use as part of a system for high-power microwave generation or for oil well exploration and as a driver for basic physics experiments, among a variety of military applications.

Additional information on explosively driven pulsed power can be found in [12] and [13].

C. Further Reading

In addition to the classic references cited in the reference list of [1], the interested reader can find additional references online, including textbooks that discuss specific aspects of pulsed power for specific applications [14], [15] and a pulsed power formulary [16].

Another important area within a broader context of pulsed power that is beyond the scope of this Special Issue has to do with megajoule, megaampere systems with current rise times on the order of $dI/dt > 1\ \mathrm{kA}/\mu\mathrm{s}$ for railguns and other electromagnetic launch systems. The reader is referred to [17] for additional information.

The premier conference sponsored by the IEEE Nuclear and Plasma Sciences Society's Pulsed Power Science and Technology Committee [18] is the biennial IEEE International Pulsed Power Conference, which also publishes conference papers in a proceedings. The next conference will be in Monterey, CA, in June 2005. The IEEE Technically Cosponsored Power Modulator Symposium has been a conference that had traditionally focused more on aspects pertaining to repetitive pulsed power. This conference also publishes a Technical Digest.

The IEEE TRANSACTIONS ON PLASMA SCIENCE has been publishing a biennial special issue devoted to pulsed power science and technology since 1997, partly derived from papers presented at the preceding IEEE International Pulsed Power Conference. The next Special Issue will be published in October 2004.

Finally, it would be a disservice not to mention the passing of J. C. "Charlie" Martin in 1999. He was a "totally unforgettable character who left no person who met him unchanged."[2] The 12th IEEE International Pulsed Power Conference held a tribute to Charlie, and his biography and tributes from colleagues were published in [19]. Additional technical publications by Charlie were compiled in [20].

REFERENCES

[1] J. C. Martin, "Nanosecond pulse techniques," *Proc. IEEE*, vol. 80, pp. 934–945, June 1992.

[2] D. Price, S. Ashby, E. Goldman, J. Swegle, G. Frazier, and J. Benford, "Heimdall models," Phys. Int. Co., San Leandro, CA, Rep. PIFR-4586, 1995.

[3] G. N. Glasoe and J. V. Lebacqz, *Pulse Generators*, ser. MIT Radiation Laboratory Series. New York: McGraw-Hill, 1948, vol. 5.

[4] M. V. Fazio and H. C. Kirbie, "Ultracompact pulsed power," *Proc. IEEE*, vol. 92, pp. 1195–1202, July 2004.

[5] Another dramatic climb toward fusion conditions for Sandia Z accelerator [Online]. Available: http://www.sandia.gov/media/z290.htm

[6] R. C. Davidson, *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*. Washington, DC: The National Academies Press, 2003.

[7] I. Langmuir, "Electric-discharge-controlling device and method of operating the same," U. S. Patent 1 289 823, Dec. 31, 1918.

[8] I. Langmuir, "The interaction of electron and positive ion space charges in cathode sheaths," *Phys. Rev.*, vol. 33, no. , pp. 954–989, 1929.

[9] S. Goldberg and J. Rothstein, "Hydrogen thyratrons," *Adv. Elect. Elec. Phys.*, vol. 14, pp. 207–264, 1961.

[10] W. Hartmann and M. A. Gundersen, "Origin of anomalous emission in superdense glow discharge," *Phys. Rev. Lett.*, vol. 60, pp. 2371–2374, 1988.

[11] "Special Issue on power electronics technology," *Proc. IEEE*, vol. 89, pp. 797–988, June 2001.

[12] A. Neuber and J. Dickens, "Magnetic flux compression generators," *Proc. IEEE*, vol. 92, pp. 1203–1213, July 2004.

[13] L. L. Altgilbers, M. D. J. Brown, I. Grishnaev, B. M. Novac, I. R. Smith, I. Tkach, and Y. Tkach, *Magnetocumulative Generators*. New York: Springer-Verlag, 2000.

[14] S. Humphries, Jr. *Principles of Charged Particle Acceleration* [Online]. Available: http://www.fieldp.com/cpa/cpa.html

[15] ——, *Charged Particle Beams* [Online]. Available: http://www.fieldp.com/cpb/cpb.html

[16] North Star Research Corporation [Online]. Available: http://www.northstar-research.com/PDF/Formweb1.pdf

[17] I. R. McNab, "Developments in pulsed power technology," *IEEE Trans. Magn.*, vol. 37, pp. 375–378, Jan. 2001.

[18] Pulsed power science and technology [Online]. Available: http://www.eece.unm.edu/ppst/ppst/index.htm

[19] I. Smith *et al.*, "Tribute to J.C. 'Charlie' Martin," in *Proc. 12th IEEE Int. Pulsed Power Conf.*, vol. 1, 1999, pp. 45–84.

[20] T. J. Martin, A. H. Guenther, and M. Kristiansen, Eds., *J. C. Martin on Pulsed Power*. New York, NY: Plenum Press, 1996.

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Dr. Schamiloglu has received the Sandia National Laboratories Research Excellence Award as part of the Delphi/Minerva team in 1991, the UNM School of Engineering Research Excellence Award twice (junior faculty in 1992 and senior faculty in 2001), and the titles of UNM Regents' Lecturer (1996) and Gardner-Zemke Professor (2000). He is an Associate Editor of the IEEE TRANSACTIONS ON PLASMA SCIENCE and has served on a National Academies Panel on Directed Energy Testing.

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[2] M. Goodman, OBE, Retired, Atomic Weapons Establishment, Aldermaston, U.K., "J.C. 'Charlie' Martin: A UK Tribute," in [19, pp. 47–56].

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