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<b>14. ABSTRACT SUBJECT (Maximum 200 Words)</b> This research final report covers activities conducted by Texas Tech University from June 1, 2000 to May 31, 2003 on Grant No. F46620-00-1-0221. We investigated the fundamental basic materials limitations to the design of compact, expendable (i.e. one-time use), pulsed power and microwave sources which can be munitions launched, air dropped, towed, etc. These devices are driven by explosives. The main devices of interest include ferromagnetic generators (FMGs), piezoelectric generators (PEGs), and two-stage systems consists of FMG and PEG as primary sources and flux compression generators (FCG) as a pulsed power amplifier. Additional research was focused on the investigations of limitations of electronic components (resistors, capacitors and batteries) to determine which are the best for designing short-time use portable pulsed power systems. The overall goal of the research was to obtain a basic physical understanding of compact generating systems and to establish the fundamental materials limits to their function, taking advantage of thermal and kinetic inertia, one-time dielectric stresses, etc. The longer term, practical goal is to obtain engineering guidelines for developing order of magnitude smaller devices than are possible with present-day, long life, high reliability generators.					
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Final Research Report  
On  
**Compact Pulsed Power and High Power  
Microwave Devices**

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## INTRODUCTION

This New World Vistas Program on Compact Pulsed Power and High Power Microwave Devices has involved two faculty members and two research professors. The personnel involved were:

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Three undergraduate students and two graduate students were involved in research in this project.

The main activities under this program were as follows:

- a. Fundamental limits to explosive-driven, compact and ultracompact high-current, high-voltage sources of primary power utilizing shock wave demagnetization of hard ferromagnetic materials and shock wave depolarization of poled piezoelectric materials.
- b. Conversion of kinetic to electric energy utilizing ferromagnetic effects.
- c. Fundamentals of completely explosive autonomous two-stage systems consisting of a ferromagnetic generator as primary source and a magnetic flux compression generator as a pulsed power amplifier.
- d. Determination of ultimate performance limits of electrical components (capacitors, resistors, batteries, etc.) for short life use.

## EXECUTIVE SUMMARY

### New Results / Accomplishments

Two novel basic concepts for generation of primary power were invented and developed under the project. The first concept is based on new fundamental effects of solid-state physics which appeared under the action of shock waves on high-energy hard ferromagnetic materials.

The second concept is based on conversion the kinetic energy of rectilinear motion of hard ferromagnetic projectile into the energy of high-voltage and high-current pulses.

The third type of generators of primary power developed under the project is based on the shock wave depolarization of piezoelectric ceramics.

Explosive facilities for small amounts of high explosives were designed and constructed which include a tank for explosive tests with diagnostic ports and a unique signal recording system for operation under high explosives.

A total of 247 explosive tests were performed with high-current and high-voltage ultracompact shock wave ferromagnetic generators (FMGs). As a result of the extensive research:

- New physical effects of longitudinal shock wave (shock wave propagates along the magnetization vector) demagnetization of  $\text{BaFe}_{12}\text{O}_{19}$  hard ferrimagnets and  $\text{Nd}_2\text{Fe}_{14}\text{B}$  high-energy hard ferromagnets were registered for the first time.
- A new physical effect of demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  hard ferromagnets under the action of transverse shock wave (shock wave propagates across the magnetization vector) was registered for the first time.
- A series of ultracompact (9 to 100  $\text{cm}^3$  in volume) high-current explosive-driven sources of primary power based on transverse shock wave demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  with output current up to 10.3 kA was designed, built and tested.
- A series of ultracompact explosive-driven generators of high-voltage (up to 22.5 kV) based on longitudinal and transverse shock wave demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  operating with extremely small amount (0.5 to 3 grams) of C-4 high explosives was designed, built and tested.

For the first time we have demonstrated the feasibility of an autonomous completely explosive two-stage pulsed power system that harnesses successively two physical phenomena: the transverse shock wave demagnetization of the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  high-energy hard ferromagnets and magnetic cumulation (magnetic flux compression). A series of completely explosive two-stage pulsed power mini-systems containing a transverse shock wave FMG as a source of primary power and a helical magnetic flux compression generator (MFCG) as a pulsed power amplifier was designed, built and tested.

The methodology of digital simulation of electrical operation of the FMG and combined FMG/MFCG system using PSpice code was developed. The developed methodology provides correct prediction of output parameters in electrical circuit of explosive-driven pulsed power systems.

A total of 754 tests were performed with high-voltage and high-current moving magnet pulsed generating systems using light gas gun and explosive operation. Detailed computer simulations of electrical and mechanical operation of the generators were carried out. As a result of this extensive research explosive-driven moving magnet generators with lengths 32 cm and diameter 3.5 cm, operating with 15 grams of explosives were developed. Developed generators are capable of producing a series of high-current pulses with amplitude from 0.85 to 3.6 kA. Using the high-voltage integrating mode made it possible to generate high-voltage pulses with amplitudes up to several tens of kilovolts.

A total of 94 explosive tests were performed with high-voltage and high-power ultracompact shock wave ferroelectric generators (FEGs) of various designs. The developed pulsed generators based on the longitudinal shock-wave depolarization of PZT EC-64 piezoelectric ceramic disks of volume 0.35 to 3.2 cm<sup>3</sup> are capable of producing pulses of high power with amplitude up to 0.34 MW and pulses of high voltage with amplitude up to 27 kV. A novel theoretical model of the explosive-driven FEG based on well-documented experimental data obtained by our research group was developed in collaboration with Dr. Larry L. Altgilbers (US Army Missile Defense Command).

Extensive experimental research and detailed computer simulations of operation of explosive-driven pulsed power systems made it possible to develop ultracompact high-efficiency generators and develop fundamentals for compact autonomous sources of primary power. Output parameters of the developed generators are more than one order higher than output parameters of all known sources of primary power.

The results of this research were published in 11 referred articles and 22 conference proceedings papers. More than 30 conference presentations were made. One patent is under preparation in the Air Force Office of Scientific Research.

The obtained results were presented to engineers, researchers and managers of US defense companies and enterprises at the Pulsed Power Short Course (TTU, Lubbock, TX, January 6-11, 2002), Explosive Pulsed Power Short Course (Chine Lake, CA, Naval Air Warfare Research Center, September 16-17, 2002) and Naval Postgraduate School (November 12, 2002).

Another line of research under this project was aimed at studying fundamental limits to electronic components. The knowledge of operation of electronic components beyond the boundaries set by the manufacturer's data sheet is extremely important for designing compact pulsed power devices intended to operate for a brief period of time.

- Two experimental setups were designed and constructed for high-current and high-voltage testing of resistors.
- Two experimental setups were designed and built for DC and pulsed high-voltage overstressing of capacitors.
- An experimental setup was designed and built for high-current overstressing of batteries.
- 827 experimental tests were performed with: (1) 12 different types of capacitors of various nominal voltage up to 16 kV produced by 7 different manufacturers; (2) four different types

of resistors of various power ratings produced by 7 different manufacturers; (3) 14 types of batteries of different chemistry and various dimensions produced by 12 different manufacturers.

Extensive experimental research made it possible to determine fundamental limits to electronic components and determine a few types of many high-voltage capacitors, resistors and batteries which are the best for compact pulsed power applications. The mechanisms of failure under overstress conditions for capacitors and resistors were studied.

- It was determined that the energy stored in TDL MICAP capacitors for a short time under overstress conditions is more than 20 times higher their nominal energy.
- It was shown that Allen Bradley carbon composition resistors of nominal ratings 1 to 5 watts can hold up to 10 megawatts power during several tens of microseconds.
- It was found out that the best battery chemistry for compact pulsed power systems is lead acid (Bolder) and lithium ion (SAFT).

These results made significant impact on the design of compact pulsed power systems and opened ways to make them smaller, lighter and more reliable in operation for brief periods of time. Moreover, it makes a significant impact upon the electronics industry to improve design of components for special applications. The results of the research were published in 8 papers. The fundamental limitations to electronic components were presented to engineers, researchers and managers from US companies and enterprises during Pulsed Power Short Course (TTU, Lubbock, TX, January 6-11, 2002). All obtained results are already used by US R&D companies (Applied Physical Electronics, Inc. and others) for development of compact Marx generators.

## SUMMARY OF COLLABORATIVE ACTIVITIES

1. M. Kristiansen, J. Dickens and S. Shkuratov attended the IEEE International Conference on Plasma Science in New Orleans, LA on July 4-7, 2000 and presented a paper entitled "Pulsed Generators Based on Shock Demagnetization of Ferromagnetic Materials".
2. M. Kristiansen and J. Dickens attended the 12<sup>th</sup> Symposium on High Current Electronics in Tomsk, Siberia on September 25-30, 2000. M. Kristiansen chaired the session on Generation of Pulsed High Voltage and Current and presented a paper entitled "Energy Balance of the Explosive-Driven Ferromagnetic Generators" (S. I. Shkuratov was co-author).
3. M. Kristiansen and J. Dickens attended the SAE (Engineering Society for Advanced Mobility Land, Sea, Air and Space International Conference) in San Diego, CA on November 31-December 2, 2000, gave short course on Explosive Pulsed Power. M. Kristiansen presented the paper entitled "Air Force Basic Research Program in Pulsed Power" (J. Agee, and J. Gaudet were co-authors).
4. M. Kristiansen attended the Radio Frequency Munitions Conference (Huntsville, AL, November 2000) under the auspices of the Advanced Technology Directorate of the U.S. Army Space and Missile Defense Command.
5. M. Kristiansen attended the Tenth National Conference on High Power Microwave Technology in Baltimore, MD (January 2001) and presented a paper entitled "Experimental Study of Compact Explosive-Driven Shock Wave Ferroelectric Generators" (S. I. Shkuratov and J.C. Dickens were co-authors).
6. M. Kristiansen, J. Dickens and S. Shkuratov attended the 13<sup>th</sup> IEEE International Pulsed Power Conference in Las Vegas, Nevada on June 17-21, 2001 and presented eight papers devoted to explosive-driven compact pulsed power sources and electronic component overstresses.
7. TTU hosted Mr. Tom Matty of the SAFT R&D Center on June 24-25, 2001 for joint high-current testing of SAFT batteries.
8. M. Kristiansen and J. Dickens attended the Direct Energy for the 21<sup>st</sup> Century, 4<sup>th</sup> Annual Directed Energy Symposium, Huntsville, AL, October 29 - November 1, 2001 and presented two papers entitled "Compact Explosive-Driven Ferromagnetic and Ferroelectric Generators" and "High Power Testing of Electronic Components" (S. I. Shkuratov and E.F. Talantsev were co-authors).
9. S.I. Shkuratov, J.C. Dickens, E.F. Talantsev attended the 14<sup>th</sup> International Conference on High-Power Particle Beams and 5<sup>th</sup> International Conference on Dense Z-Pinches, Albuquerque, New Mexico, USA, June 23-28, 2002 and presented five papers (M. Kristiansen was co-author).

10. S. I. Shkuratov, E.F. Talantsev, J.C. Dickens and M. Kristiansen attended the 9<sup>th</sup> International Conference on High Megagauss Magnetic Field Generation and Related Topics, July 7-14, 2002 and presented eleven papers.
11. M. Kristiansen, J. Dickens, S.I. Shkuratov and E.F. Talantsev gave four lectures during short course on Explosive Pulsed Power and Electronic Component Overstresses of Texas Tech University, Lubbock, TX on January 7-11, 2002.
12. M. Kristiansen and J. Dickens gave a short course on Explosive Pulsed Power and Electronic Component Overstresses for Bechtel Corp., Las Vegas, March 2002.
13. S.I. Shkuratov visited University of Missouri at Columbia and gave a presentation on Explosive Driven Pulsed Power Sources (April 14, 2003).
14. S.I. Shkuratov visited University of Missouri-Rolla and gave two presentations on Explosive Driven Pulsed Power and Electronics Components for Compact Pulsed Power (April 15, 2003).
15. M. Kristiansen, J. Dickens and S. Shkuratov attended the 14<sup>th</sup> IEEE International Pulsed Power Conference in Dallas, Texas on June 18-21, 2003 and presented four papers devoted to explosive-driven compact pulsed power sources and electronic component overstresses.

#### NEW WORLD VISTAS SYNERGISM WITH OTHER RESEARCH PROGRAMS

This New World Vistas program is closely related to TTU's MURI/AFOSR program on Explosive-Driven Pulsed Power Generation funded by the Director of Defense Research and Engineering (DDR&E) and managed by the Air Force Office of Scientific Research (AFOSR).

The New World Vistas ultracompact high-current explosive driven sources of primary power based on transverse shock wave demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  high-energy hard ferromagnetics were used for the first time as seed sources for magnetic flux compression generators developed in MURI/AFOSR program on Explosive-Driven Pulsed Power Generation.

Dr. Larry Altgilbers (U.S. Army Space and Missile Defense Command, Huntsville, AL), Dr. Forrest Agee (Physics and Electronics Directorate, Air Force Research Laboratory, Air Force Office of Scientific Research, Arlington, VA), Col. Joseph A. Gregor (Air Force Office of Scientific Research, Washington, D.C.), Capt. Karl R. Young (Naval Air Warfare Center, China Lake, CA), Dr. Michael G. Grothaus (RF Engineering Section of the Southwest Research Institute, San Antonio, TX), W. Mark Henderson (Directed Energy Test Director, Naval Air Warfare Center, China Lake, CA), Donald Littrell (AFRL/MNMI, Eglin Air Force Base, FL), Kenneth S. Jensen (Special Project Office, Kansas City Plant, Operated by Honeywell for the U.S. Department of Energy's, Kansas City, MO) were kept continually updated on our research progress and received copies of all our reports and papers.

1. **TTU hosted (from January 6 to January 11, 2002) "Pulsed Power Short Course".** 44 employees from US companies, enterprises, US and Singapore defense organizations were participants in the Short Course.

The New World Vistas presentations at the Short Course included 4 oral presentations on the topics:

- A. Explosive Driven Ferromagnetic Generators.
- B. Explosive Driven Piezoelectric Generators.
- C. Explosive Driven Moving Magnet Generators.
- D. Light Gas Gun Moving Magnet Generators.
- E. High-Current Mode for Testing Batteries.
- F. High-Voltage Repetitive and Group Testing of Capacitors.
- G. High-Current Mode for Testing Resistors.

Two experimental tests with light gas gun moving magnet system were performed for participants of the "Short Course".

2. **TTU hosted (April 12, 2002) for joint workshop:**

- A. Mr. Sten Johansson (Senior Program Manager Technologies), Mr. Per Johansson (Sales Director, Market Development), Mr. Magnus Karlsson (Research Engineer) of the BOFORS DEFENSE AB, a United Defense Company, Sweden
- B. Mr. Gert Bjarnholt (Assistant Director of Research) of the Division of Weapons and Protection of the Department of Ballistics and RF Weapons, Defense Research Establishment, FOA, Sweden
- C. Dr. John Mayes and Mr. W.J. Carey of the Applied Physical Electronics, Austin, TX.

The New World Vistas oral presentation at the workshop included the topics:

- A. Explosive Driven Piezoelectric Generators.
- B. Explosive Driven Ferromagnetic Generators.
- C. Explosive Driven Moving Magnet Generators.
- D. Light Gas Gun Moving Magnet Generators.
- E. High-Current Mode for Testing Batteries.
- F. High-Voltage Testing of Capacitors for Portable Arkadiev-Marx Generator.
- G. High-Current Mode for Testing Resistors.

An explosive test for pulsed power generation by an explosive-driven generator based on a longitudinal shock wave demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  high-energy hard ferromagnetics was demonstrated.

**3. TTU hosted (February 26, 2002) for joint workshop:**

- A. Dr. Michael G. Grothaus (RF Engineering Section) of the Southwest Research Institute, San Antonio, TX.
- B. Dr. Steve Calico (Directed Energy Technologies) of Lockheed Martin Aeronautic Company, Fort Worth, TX.

The New World Vistas oral presentation on the workshop included the next topics:

- A. Explosive Driven Piezoelectric Generators.
- B. Explosive Driven Ferromagnetic Generators.
- C. Explosive Driven Moving Magnet Generators.
- D. Light Gas Gun Moving Magnet Generators.
- E. High-Current Mode for Testing Batteries.
- F. High-Voltage Testing of Capacitors for Portable Arkadiev-Marx Generator.
- G. High-Current Mode for Testing Resistors.

Two real explosive tests of pulsed power generation by an explosive-driven generator based on a transverse shock wave demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  high-energy hard ferromagnetics were demonstrated.

**4. TTU hosted (March 15, 2002) Dr. John Mayes of Applied Physical Electronics Inc. (March 15, 2002) for workshop about High-Power Microwave Radiation.**

The NWV's presentation on the workshop included the topics

- H. High-Current Mode for Testing Batteries.
- I. High-Voltage Testing of Capacitors for Portable Arkadiev-Marx Generator.

**5. TTU hosted (August 16, 2002) for workshop: Annual Review of MURI Program on Explosive-Driven Power Generation for Directed-Energy Munitions.**

- a. Col. Joseph A. Gregor of the Air Force Office of Scientific Research, Washington, D.C.
- b. Dr. Larry Altgilbers of the U.S. Army Space and Missile Defense Command, Huntsville, AL.
- c. Capt. Karl S. Young of Directed Energy NAWCWD –China Lake, CA.
- d. Dr. Donald Littrell of the AFRL/MNMI, Eglin Air Force Base, FL.
- e. Dr. Steve Calico (Directed Energy Technologies) of Lockheed Martin Aeronautic Company, Fort Worth, TX.
- f. Mark Lehr, Air Force Phillips Laboratories/Phillips Site.

A New World Vistas oral presentation at the workshop included the next topics:

- A. Completely Explosive Driven Pulsed Power Mini-Systems.
- B. Explosive Driven Ferromagnetic Generators.
- C. Explosive Driven Piezoelectric Generators.
- D. Light Gas Gun Moving Magnet Generators.

This presentation was for information purpose.

A real (ready to fire) completely explosive pulsed power mini-system was demonstrated in the Explosive Facility of the Center for Pulsed Power and Power Electronics, TTU.

**6. Short-term project of TTU New World Vistas and TTU Explosive MURI programs with U.S. Naval Air Warfare Center (China Lake, CA) (September-October 2002).**

In frame of this project the short course was organized for researchers, engineers and managers of Naval Air Warfare Center. The short course was conducted in China Lake, CA on September 17-18, 2002. The New World Vistas presentations at the Short Course included 2 oral presentations on the topics:

- A. Explosive Driven Ferromagnetic Generators.
- B. Explosive Driven Piezoelectric Generators.

Nine ultracompact shock wave ferromagnetic and shock wave ferroelectric generators of primary power of different designs were developed for NAWC. Each generator had complete documentation including detailed description of the device, detailed drawings, electrical schematics and detailed instruction of the explosive test setup.

## SUMMARY OF PUBLISHING ACTIVITIES

### PATENT

“Method for Producing Pulses of Primary Power by Ferromagnetic Pulsed Generators”, S.I. Shkuratov, E.F. Talantsev, J.C. Dickens, M. Kristiansen and R.J. Barker, Patent is pending by U.S. Air Force Office of Scientific Research (2003).

### JOURNAL PAPERS

1. “Pulse Generation Using Open and Closed Ferromagnetic Circuits”, S.I. Shkuratov, M. Kristiansen, J. Dickens, L.L. Hatfield, and R. Martin, *IEEE Transactions on Plasma Science* **28** (2000) 1347-1352.
2. “High Current and High Voltage Pulsed Testing of Resistors”, S.I. Shkuratov, M. Kristiansen, J. Dickens, L.L. Hatfield, and E. Horrocks, *IEEE Transactions on Plasma Science* **28** (2000) 1607-1614.
3. “Single-Shot, Repetitive and Life-Time High Voltage Testing of Capacitors”, S.I. Shkuratov, E.F. Talantsev, L.L. Hatfield, J.C. Dickens, and M. Kristiansen, *IEEE Transactions on Plasma Science*, Special Issue on Pulsed Power Science and Technology, **30**, No. 5 (2002) 1674-1680.
4. “Current Mode of Pulsed Power Generation in Moving Magnet Systems”, S.I. Shkuratov, J. Dickens, M. Kristiansen, and J.C. Hernandez, *IEEE Transactions on Plasma Science*, Special Issue on Pulsed Power Science and Technology, **30**, No. 5 (2002) 1943-1949.
5. “Compact Explosive-Driven Generator of Primary Power Based on a Longitudinal Shock Wave Demagnetization of Hard Ferri- and Ferromagnets”, S.I. Shkuratov, E.F. Talantsev, J.C. Dickens, and M. Kristiansen, *IEEE Transactions on Plasma Science*, Special Issue on Pulsed Power Science and Technology, **30**, No. 5 (2002) 1681-1691.
6. “Theoretical Treatment of Explosive Driven Ferroelectric Generators”, Y. Tkach, S.I. Shkuratov, E.F. Talantsev, M. Kristiansen, J. Dickens, L.L. Altgilbers, and P.T. Tracy, *IEEE Transactions on Plasma Science*, Special Issue on Pulsed Power Science and Technology, **30**, No. 5 (2002) 1665-1673.
7. “Shock Wave Demagnetization of BaFe<sub>12</sub>O<sub>19</sub> Hard Ferrimagnetics”, S.I. Shkuratov, E.F. Talantsev, J. Dickens, M. Kristiansen, *Journal of Applied Physics*, **91** (2002) 3007-3009.
8. “Transverse Shock Wave Demagnetization of Nd<sub>2</sub>Fe<sub>14</sub>B High-Energy Hard Ferromagnetics”, S.I. Shkuratov, E.F. Talantsev, J. Dickens, M. Kristiansen, *Journal of Applied Physics*, **92** (2002) 159-162.

9. "Ultracompact Explosive-Driven High-Current Source of Primary Power Based on Shock Wave Demagnetization of Nd<sub>2</sub>Fe<sub>14</sub>B Hard Ferromagnetics", S.I. Shkuratov, E.F. Talantsev, J. Dickens, M. Kristiansen, *Review of Scientific Instruments*, **73** (2002) 2738-2742.
10. "The Conductivity of a Longitudinal-Shock-Wave-Compressed Nd<sub>2</sub>Fe<sub>14</sub>B Hard Ferromagnetics", E.F. Talantsev, S.I. Shkuratov, J. Dickens, M. Kristiansen, *Modern Physics Letters B*, **16**, No. 15&16 (2002) 545-554.
11. "Longitudinal Shock Wave Demagnetization of High Energy Nd<sub>2</sub>Fe<sub>14</sub>B Ferromagnetics", S.I. Shkuratov, E.F. Talantsev, J.C. Dickens, M. Kristiansen. *Applied Physics Letters*, **82** (2003) 1248-1250.
12. "Completely Explosive Pulsed Power Mini-System", E.F. Talantsev, S.I. Shkuratov, J. Dickens, M. Kristiansen. *Review of Scientific Instruments*, **74**, No. 1, Part I (2003) 225-230.
13. "Currents Produced by Explosive Driven Transverse Shock Wave Ferromagnetic Source of Primary Power in a Coaxial Single-Turn Seeding Coil of a Magnetocumulative Generator", S.I. Shkuratov, E.F. Talantsev, J.C. Dickens, M. Kristiansen, *Journal of Applied Physics*, **93** (2003) 4529-4535.

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2. "Pulsed Generators Based on Shock Demagnetization of Ferromagnetic Materials", S.I. Shkuratov, M. Kristiansen, and J. Dickens, Book of Abstracts of 27<sup>th</sup> IEEE International Conference on Plasma Science, New Orleans, LA, June 2000, p. 277.
3. "Experimental Study of Compact Explosive-Driven Shock Wave Ferroelectric Generators", S.I. Shkuratov, M. Kristiansen, J. Dickens, A.A. Neuber, L.L. Altgilbers, P.T. Tracy, Y. Tkach, Proceedings of 13<sup>th</sup> IEEE International Pulsed Power Conference, Las Vegas, Nevada, June 2001, p. 227.
4. "Explosive-Driven Moving Magnet Generators", S.I. Shkuratov, M. Kristiansen, J. Dickens, Proceedings of 13<sup>th</sup> IEEE International Pulsed Power Conference, Las Vegas, Nevada, June 2001, p. 227.
5. "The Charging and Integrating Modes of Pulsed Power Generation in Moving Magnet Systems", S.I. Shkuratov, M. Kristiansen, J. Dickens, J.C. Hernandez, Proceedings of 13<sup>th</sup> IEEE International Pulsed Power Conference, Las Vegas, Nevada, June 2001, p. 228.
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## **APPENDIX**

The following appendix lists the abstracts for patent and papers published in refereed journals.

*The patent is pending by the Air Force Office of Scientific Research (2003).*

## **ABSTRACT #1**

### **Method for Producing Pulses of Primary Power by Ferromagnetic Pulsed Generators**

Sergey I. Shkuratov, Lubbock, TX, Evgueni F. Talantsev, Lubbock, TX, James C. Dickens, Lubbock, TX, Magne Kristiansen, Lubbock, TX, Robert J. Barker, Arlington, VA

#### **ABSTRACT**

A generator of primary power includes a magnetic flux carrier, an explosive charge or accelerated body, and a pulse-generating coil. The magnetic flux carrier is made, completely or partially, of ferromagnetic materials and can be designed as an element of open or closed magnetic circuit. An action of the explosive charge on the magnetic flux carrier or a collision of an accelerated body with the magnetic flux carrier initiates the "ferromagnetic-to-nonferromagnetic" or "ferrimagnetic-to-nonferrimagnetic" phase transition in the magnetic flux carrier. The phase transition results in a partial or complete loss of the initial magnetic flux stored in the magnetic flux carrier. This change in magnetic flux, according to Faraday's law, generates a pulsed electromotive force in the pulse-generating coil. The pulsed electromotive force generated causes the appearance of electric current and/or voltage in the pulse-generating coil and load circuits. The output pulse peak current, peak voltage, duration and power are determined by the material, shape and quantity of the magnetic flux carriers, ways of action on the magnetic flux carriers, the electrical parameters of the of the pulse-generating coil and load circuits.

**ABSTRACT #2**

**Pulse Generation Using Open and Closed Ferromagnetic Circuits\***

S.I. Shkuratov, M. Kristiansen, J. Dickens, L.L. Hatfield, and R. Martin  
*Center for Pulsed Power and Power Electronics Department of Electrical and Computer  
Engineering Texas Tech University, Lubbock, TX 79409-3102*

**ABSTRACT**

Results are presented of an experimental study of the generation of high-voltage and high-current pulses in generators designed as open and closed ferromagnetic circuits. Experiments were carried out using a light gas gun system. The magnetic projectiles were composed of ferromagnetic disks having 1.27 and 2.54-cm diameters. It has been shown that with velocities of the magnetic projectiles of 200-380 m/s, the peak voltage of the pulses produced by the generators reach several tens of kilovolts, peak current reaches kiloampere and the energy delivered at the load is a few Joules. Generating modules connected in series will make it possible to produce a high energy pulse with a peak voltage of a few hundred kV. It has been shown that a closed ferromagnetic circuit generator is capable of generating not only single high voltage pulses, but also repetitive oscillations. Data are given for the effects on the amplitude of high voltage pulses caused by the length and velocity of the ferromagnetic projectiles and the design of the generating unit for both high voltage and high current modes of pulsed power generation.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

**ABSTRACT #3**

**High Current and High Voltage Pulsed Testing of Resistors\***

S.I. Shkuratov, M. Kristiansen, J. Dickens, L.L. Hatfield, and E. Horrocks

**ABSTRACT**

Three types of resistors have been tested to determine maximum usable power at pulsed high voltage and pulsed high current. Experiments were carried out using high voltage cable generators, spark-gap generators and thyatron drivers. Pulse durations were varied from 0.7  $\mu$ s to 21  $\mu$ s. The pulse amplitudes were varied from 1 kV to 35 kV. The peak current reached was 3 kA. Metal film, carbon film and carbon composition resistors of four different rated powers (0.25 W, 0.5 W, 1 W, 2 W) have been tested. Data are given for the limiting pulsed power and energy for each type of resistor in nanosecond and microsecond time ranges. The experimental investigation of the threshold loading of the resistors in the high current pulsed mode and in the high voltage pulsed mode has shown that the process of destruction of resistors has specific features for each mode. The mechanisms of failure and destruction of resistors under the action of high voltage and high current pulses are discussed.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

**ABSTRACT #4**

**Shock Wave Demagnetization of  $\text{BaFe}_{12}\text{O}_{19}$  Hard Ferrimagnetics\***

S.I. Shkuratov, E.F. Talantsev, J.C. Dickens, and M. Kristiansen  
*Center for Pulsed Power and Power Electronics Department of Electrical and Computer  
Engineering Texas Tech University, Lubbock, TX 79409-3102*

**ABSTRACT**

A study of the effect of shock waves on the phase state of a hard ferrimagnetic material has been performed. A plane shock wave was passed along the axis of a cylindrical  $\text{BaFe}_{12}\text{O}_{19}$  hard ferrite magnet. The shock wave demagnetized the cylinder, reducing the magnetic flux. This change in magnetic flux generated an electromotive force (EMF) in a coil wound around the ferrite. The value of the EMF calculated on the assumption that the ferrite was completely demagnetized by the shock wave is in good agreement with the EMF value obtained experimentally. The new physical phenomenon of shock wave demagnetization of hard ferrimagnetics was registered for the first time.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

**ABSTRACT #5**

**Transverse Shock Wave Demagnetization of Nd<sub>2</sub>Fe<sub>14</sub>B High-Energy Hard Ferromagnetics\***

Sergey I. Shkuratov, Evgueni F. Talantsev, James C. Dickens and Magne Kristiansen  
*Center for Pulsed Power and Power Electronics Department of Electrical and Computer  
Engineering, Texas Tech University, Lubbock, TX 79409-3102*

**ABSTRACT**

The action of transverse shock waves (the shock wave propagates across the magnetization vector  $M$ ) on the magnetic phase state of a Nd<sub>2</sub>Fe<sub>14</sub>B high-energy hard ferromagnetics was investigated experimentally. The design of the ferromagnetic sample, which was made for the first time as a hollow cylinder, has made it possible to reduce dramatically the amount of the explosive initiating a transverse shock wave in Nd<sub>2</sub>Fe<sub>14</sub>B to 1.0 g (for Nd<sub>2</sub>Fe<sub>14</sub>B samples of weight 67.5 g). The results of the experiment have shown that the transverse shock wave propagating through Nd<sub>2</sub>Fe<sub>14</sub>B causes the "hard ferromagnetic-to-paramagnetic" phase transformation terminating by practically complete demagnetization of Nd<sub>2</sub>Fe<sub>14</sub>B. The pulse generators based on the transverse shock-wave demagnetization of hollow cylindrical Nd<sub>2</sub>Fe<sub>14</sub>B samples of diameter 2.54 cm and length 1.905 cm are capable of producing high-voltage pulses (peak voltage 11.3 kV, FWHM 4.5  $\mu$ s) and high-current pulses (peak current 1.93 kA, FWHM 100  $\mu$ s, peak power 27.0 kW). A new physical effect – transverse shock wave demagnetization of high-energy hard ferromagnetics Nd<sub>2</sub>Fe<sub>14</sub>B – has been detected for the first time.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

**ABSTRACT #6**

**Ultracompact Explosive-Driven High-Current Pulsed Power Source Based on Shock Wave Demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  Hard Ferromagnetics\***

S.I. Shkuratov, E.F. Talantsev, J.C. Dickens, and M. Kristiansen  
*Center for Pulsed Power and Power Electronics, Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX 79409-3102*

**ABSTRACT**

A new type of explosive driven high-current pulsed source utilizing a shock wave demagnetization of an  $\text{Nd}_2\text{Fe}_{14}\text{B}$  hard ferromagnetic energy carrier was developed. The design of the ferromagnetic energy carrier, which was made for the first time as a hollow cylinder, has made it possible to reduce dramatically to 1 g the amount of the explosive providing a complete demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  energy carrier of weight 68 g. The developed generator is capable of producing high-current (up to 1.9 kA, 100  $\mu\text{s}$  FWHM) and high-power pulses (up to 42 kW, 2.8  $\mu\text{s}$  FWHM).

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

ABSTRACT #7

**The Conductivity of a Longitudinal-Shock-Wave-Compressed  
Nd<sub>2</sub>Fe<sub>14</sub>B Hard Ferromagnetics\***

Evgueni F. Talantsev, Sergey I. Shkuratov, James C. Dickens, and Magne Kristiansen  
*Center for Pulsed Power and Power Electronics, Department of Electrical and Computer  
Engineering, Texas Tech University, Lubbock, TX 79409-3102*

ABSTRACT

The conductivity of the Nd<sub>2</sub>Fe<sub>14</sub>B hard ferromagnetic subjected to compression by a longitudinal shock wave (the shock wave propagates along the magnetization vector  $\mathbf{M}$ ) with a pressure of 35 GPa has been measured. The results of the experiments have shown that the conductivity of the longitudinal-shock-wave-compressed Nd<sub>2</sub>Fe<sub>14</sub>B is  $\sigma_{sw} = (2.83 \pm 0.24) 10^2 (\Omega \text{ cm})^{-1}$ , which is 22 times lower than the conductivity of Nd<sub>2</sub>Fe<sub>14</sub>B under normal conditions.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

**ABSTRACT #8**

**Single Shot, Repetitive, and Life-Time High Voltage Testing of Capacitors\***

Sergey I. Shkuratov, Evgueni F. Talantsev, Lynn L. Hatfield,  
James C. Dickens and Magne Kristiansen

*Center for Pulsed Power and Power Electronics, Departments of Electrical and Computer  
Engineering and Physics, Texas Tech University, Lubbock, TX 79409-3102, USA*

**ABSTRACT**

Four different types of capacitors have been tested to determine the maximum usable high voltage. Ceramic, drop dipped film, molded-mylar tubulars and polyster/foil capacitors of different values and different nominal voltages were tested in four modes: the single shot mode, the repetitive mode, the life time DC voltage mode, and the group mode. Experiments have shown that the breakdown voltage for all types of the capacitors tested is ten to seventeen times more than the nominal voltage. Data are given for the limitations for single capacitors, and for two, three and four capacitors connected in parallel. Experiments have shown that the breakdown of each type of capacitors have specific features. The mechanisms of failure and destruction of capacitors under the action of high voltage are discussed.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

**ABSTRACT #9**

**Current Mode of Pulsed Power Generation in Moving Magnet System\***

Sergey I. Shkuratov, Evgueni F. Talantsev, James C. Dickens,  
Magne Kristiansen, and Juan C. Hernandez

*Center for Pulsed Power and Power Electronics, Department of Electrical and Computer  
Engineering, Texas Tech University, Lubbock, TX 79409-3102, USA*

**ABSTRACT**

Results of an experimental study of the generation of high-current pulses in a moving magnet system based on an open ferromagnetic circuit design are presented. The magnet was accelerated with the use of a light gas gun. Experimental data are given for the output high current pulses, output voltage, and power delivered in the load for different types of pulse-generating coils. The effect of various pulse-generating windings is given. It has been shown that the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  hard ferromagnetic projectile (diameter 2.54 cm and height 1.9 cm) moving with a velocity of 300 m/s is capable to produce in the pulse-generating coil a current pulse with maximum 1.4 kA and a full width at half maximum (FWHM) 80  $\mu\text{s}$ .

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

**ABSTRACT #10**

**Theoretical Treatment of Explosive-Driven Ferroelectric Generators\***

Yaroslav Tkach\*, Sergey I. Shkuratov\*\*, Evgueni F. Talantsev, James C. Dickens\*\*, Magne  
Kristiansen\*\*, Larry L. Altgilbers\*\*\*, Philip T. Tracy\*\*\*\*

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**ABSTRACT**

As a part of the New World Vistas Program, a series of ultra-compact explosive driven ferroelectric generators (EDFEGs) have been designed, constructed and tested by Texas Tech University providing well-documented EDFEG output parameters that were used to benchmark a theoretical model of the EDFEG developed at the Institute of Electromagnetic Research. In this paper, a description of the model for the EDFEG is presented along with a brief description of the EDFEG, the experimental setup and test procedures that was used. A comparison of the experimental and calculated results showed them to be in good agreement.

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\* The TTU work was funded in part by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

ABSTRACT #11

**Compact Explosive-Driven Generator of Primary Power Based on a Longitudinal Shock Wave Demagnetization of Hard Ferri- and Ferromagnetics\***

Sergey I. Shkuratov, Evgueni F. Talantsev, James C. Dickens, and Magne Kristiansen  
*Center for Pulsed Power and Power Electronics, Departments of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX 79409-3102, USA*

ABSTRACT

A new type of compact explosive driven generators of primary power utilized phenomena of a shock wave demagnetization of hard ferri- and ferromagnetics was developed. The shock wave initiated by high explosive, as well as accelerated flyer plate, passes along the hard ferri- or ferromagnetic body served as initial energy carrier. The shock wave demagnetizes the energy-carrying element, reducing the initial magnetic flux  $\Phi_0$ . In accordance with Faraday's law, this change of magnetic flux  $\Delta\Phi_0$  generates an electromotive force in a coil wound on the energy carrier. Several types of compact generators with energy-carrying element of  $10\text{ cm}^3$  in volume were explored. High-voltage generators utilized energy of  $\text{BaFe}_{12}\text{O}_{19}$  hard ferrimagnetics produced pulses reached peak voltage 5.5 kV and full width at half maximum (FWHM) of  $1\ \mu\text{s}$ . The generators utilized energy of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  high-energy hard ferromagnetics produced pulses with peak amplitude more than 10 kV and FWHM about  $4\ \mu\text{s}$ . The high-current generators based on  $\text{Nd}_2\text{Fe}_{14}\text{B}$  produced pulses yielded 826 A and FWHM of  $180\ \mu\text{s}$ . The developed generator can be used as most reliable and effective source of primary power capable to seed magnetocumulative generators.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

**ABSTRACT #12**

**Longitudinal Shock Wave Demagnetization of High Energy  
Nd<sub>2</sub>Fe<sub>14</sub>B Ferromagnetics\***

Sergey I. Shkuratov, Evgueni F. Talantsev, James C. Dickens, and Magne Kristiansen  
*Center for Pulsed Power and Power Electronics, Department of Electrical and Computer  
Engineering, Texas Tech University, Lubbock, TX 79409-3102*

**ABSTRACT**

A study of the effect of longitudinal shock wave action (shock wave propagates along the magnetization vector  $M$ ) on the magnetic phase state of a high-energy hard ferromagnetic Nd<sub>2</sub>Fe<sub>14</sub>B has been performed. The results of the experiments have shown that a shock wave propagating through Nd<sub>2</sub>Fe<sub>14</sub>B causes the "ferromagnetic-paramagnetic" phase transformation terminating by practically complete demagnetization of Nd<sub>2</sub>Fe<sub>14</sub>B. The pulse generators based on the longitudinal shock-wave demagnetization of solid cylindrical Nd<sub>2</sub>Fe<sub>14</sub>B samples of diameter 22.2 mm and length 25.4 mm are capable of producing high-current pulses (peak current 1.0 kA, FWHM 165 μs, peak power 15.0 kW) and high-voltage pulses (peak voltage 13.4 kV, FWHM 8.2 μs). A new physical effect – longitudinal shock wave demagnetization of high-energy hard ferromagnetic Nd<sub>2</sub>Fe<sub>14</sub>B – was detected for the first time.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

- • ' *Review of Scientific Instruments*, **74**, No. 1, Part I (2003) 225-230.

### ABSTRACT #13

## **A Completely Explosive Pulsed Power Mini-System**

E.F. Talantsev, S.I. Shkuratov, J.C. Dickens, and M. Kristiansen  
*Center for Pulsed Power and Power Electronics, Department of Electrical and Computer  
Engineering, Texas Tech University, Lubbock, TX 79409-3102*

### ABSTRACT

It has been demonstrated that it is feasible to produce pulsed power using an autonomous completely explosive system that harnesses successively two physical phenomenon: the transverse shock wave demagnetization of the  $\text{Nd}_2\text{Fe}_{14}\text{B}$  high-energy hard ferromagnetic and magnetic cumulation.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)

ABSTRACT #14

**Currents Produced by Explosive-Driven Transverse Shock Wave Source of Primary Power in the Coaxial Single-Turn Seeding Coil of a Magnetocumulative Generator**

Sergey I. Shkuratov, Evgueni F. Talantsev, James C. Dickens, and Magne Kristiansen  
*Center for Pulsed Power and Power Electronics, Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX 79409-3102*

ABSTRACT

A comprehensive experimental and digital simulation study of the generation of seed current by a new type of an ultra-compact ( $8.7\text{-}25\text{ cm}^3$  in volume) explosive-driven generator of primary power loaded on the coaxial single-turn seeding coil of a magnetocumulative generator (MCG) has been performed. The operation of the ultra-compact generator (FMG) is based on transverse shock wave demagnetization of  $\text{Nd}_2\text{Fe}_{14}\text{B}$  high-energy hard ferromagnetics. The use of the design of ultra-compact FMG with energy-carrying element made as a hollow  $\text{Nd}_2\text{Fe}_{14}\text{B}$  cylinder magnetized along the axis has made it possible to reduce dramatically (to 0.6 g) the mass of the high explosive (C-4) necessary for the operation of the generator with an  $\text{Nd}_2\text{Fe}_{14}\text{B}$  energy-carrying element of mass 185.7 g. The FMG was capable of producing in the coaxial seeding coil of MCG a seed current with peak amplitude  $I(t)_{max} = 4180\text{ A}$  and full width at half maximum of  $50\text{ }\mu\text{s}$ . The methodology was developed for digital simulation of the seeding processes in the combined FMG/MCG system. Experimental results obtained are in a good agreement with results of digital calculations performed.

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\* This work was solely funded by New World Vistas Program in the Air Force Office of Scientific Research (AFOSR)