1 of 1

NOV 19 1993
OSTI

UCRL-ID 112776
Reprinted from *Engineering Research,
Development, and Technology.*
Thrust Area Report FY 92
UCRL 53868-92

Microwave and Pulsed Power

E. Karl Freytag

March, 1993

Lawrence
Livermore
National
Laboratory

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory. Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California and shall not be used for advertising or product endorsement purposes.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

Microwave and Pulsed Power

E. Karl Freytag

REPRODUCTION OF THIS DOCUMENT IS PROHIBITED

EF
MASTER

Microwave and Pulsed Power

The goals of the Microwave and Pulsed Power thrust area are to identify realizable research and development efforts and to conduct high-quality research in those pulse power and microwave technologies that support existing and emerging programmatic requirements at Lawrence Livermore National Laboratory (LLNL). Our main objective is to work on nationally important problems while enhancing our basic understanding of enabling technologies such as component design and testing, compact systems packaging, exploratory physics experiments, and advanced systems integration and performance. During FY-92, we concentrated our research efforts on the six project areas described in this report.

1. We are investigating the superior electronic and thermal properties of diamond that may make it an ideal material for a high-power, solid-state switch.

2. We are studying the feasibility of using advanced Ground Penetrating Imaging Radar technology for reliable non-destructive evaluation of bridges and other high-value concrete structures. These studies include conceptual designs, modeling, experimental verifications, and image reconstruction of simulated radar data.

3. We are exploring the efficiency of pulsed plasma processing techniques used for the removal of NO_x from various effluent sources.

4. We have finished the investigation of the properties of a magnetically delayed low-pressure gas switch, which was designed here at LLNL.

5. We are applying statistical electromagnetic theory techniques to help assess microwave effects on electronic subsystems, by using a mode stirred chamber as our measurement tool.

6. We are investigating the generation of perfluoroisobutylene (PFIB) in proposed CFC replacement fluids when they are subjected to high electrical stresses and breakdown environments.

E. Karl Freytag
Thrust Area Leader

Section 7

7. Microwave and Pulsed Power

Overview

E. Karl Freyrag, Thrust Area Leader

Pulsed Plasma Processing of Effluent Pollutants and Toxic Chemicals

George E. Vogtlin 7-1

Ground Penetrating Imaging Radar for Bridge Inspection

*John P. Warhus, Scott D. Nelson, Jose M. Hernandez,
Erik M. Johansson, Hua Lee, and Brett Douglass 7-5*

High-Average-Power, Electron Beam-Controlled Switching in Diamond

*W. Wayne Hofer, Don R. Kania, Karl H. Schoenbach,
Ravindra Joshi, and Ralf P. Brinkmann 7-13*

Testing of CFC Replacement Fluids for Arc-Induced Toxic By-Products

*W. Ray Cravey, Wayne R. Luedtka, Ruth A. Hawley-Fedder, and
Linda Foiles 7-19*

Applying Statistical Electromagnetic Theory to Mode Stirred Chamber Measurements

Richard A. Zacharias and Carlos A. Avalle 7-23

Magnetically Delayed Low-Pressure Gas Discharge Switching

*Stephen E. Sampayan, Hugh C. Kirbie, Anthony N. Payne,
Eugene Lauer, and Donald Prosnitz 7-27*

Pulsed Plasma Processing of Effluent Pollutants and Toxic Chemicals

George E. Vogtlin

*Defense Sciences Engineering Division
Electronics Engineering*

We are exploring the efficiency of pulsed plasma processing in the removal of NO_x and other pollutants. Our ultimate goal is a flow-through system where gases would be treated during a single pass. We are currently using a closed-loop system with mixtures of bottled gas. The closed-loop system permits testing of processes, without a requirement for the development of complex and expensive power supplies for the one-pass treatment. We have constructed a new processor this year that can accommodate many electrode shapes at temperatures up to 400°F .

Introduction

The efficient removal of NO_x from effluent sources is essential to meet the requirements of the Clean Air Act. NO_x is a mixture of nitric oxide, NO , and nitrogen dioxide, NO_2 . We are exploring the efficiency of pulsed plasma processing in the removal of NO_x and other pollutants. Pulsed plasma appropriate for processing is generated by a short high-voltage pulse between two electrodes. The electrons from this discharge create radicals from the air molecules. These radicals can then react with the pollutants to give harmless or removable substances.

Our ultimate goal is a flow-through system where gases would be treated during a single pass. We are currently using a closed-loop system with mixtures of bottled gas. The closed-loop system permits testing of processes, without a requirement for the development of complex and expensive power supplies for the one-pass treatment. We also believe that flow through the reactor should be in turbulent flow. Turbulent flow means that all the gases in the processor flow through at the same velocity, including that at the wall. The closed-loop system permits these high flow rates without an extensive gas-mixing and heating system.

Progress

Experimental System

The experimental system permits the introduction of various gas combinations prior to testing.

Analysis can be conducted during or after these tests. We have constructed a new processor this year that can accommodate many electrode shapes at temperatures up to 400°F . This processor is shown in Fig. 1.

Electrode geometries can have a crucial role in the efficiency of this process. It is essential to efficiently couple the energy uniformly into the gas. The geometry can affect the power supply coupling efficiency, the discharge uniformity, and the pressure losses due to turbulence.

Figure 1. Processor for removing effluent pollutants.

Figure 2.
Electrode geometry
for processor.

The processing chamber has been designed with an outer pipe two inches in diameter. This tube can be used as an electrode; other geometries of smaller dimensions can be placed inside. The reaction chamber can be increased in length as needed to match the impedance of the high voltage feed to that of the processor, for maximum energy transfer. Configurations tested for NO removal are shown in Fig. 2.

Nitric Oxide Removal

We measure the efficiency of removal in eV/molecule. The performance of the removal in eV/NO molecule is a function of the NO concentration. We are presently charging the system to approximately 600 ppmv (parts per million by volume). NO reacts with itself in the presence of air, and the change in concentration is proportional to the square of the concentration. This means that the natural rate of NO reduction at 500 ppmv is 25 times that at 100 ppmv. This effect must be subtracted from the reduction due to pulse plasma processing. The natural reduction of NO has a

negative temperature coefficient, which means the reduction is less at higher temperatures. At room temperature, the natural decay at 500 ppmv is approximately equivalent to 20-pulses-per-second pulse plasma processing. We feel the present system gives good data to the 500 ppmv level and can go to higher ppmv at higher temperatures. The efficiency of NO removal has shown to be sensitive to concentration. Figure 3 shows this effect. It appears that the removal of NO₂ increases once the NO has been removed.

Initial measurements will be made with the closed-loop system; however, we intend to convert this system to a flow-through system, which will permit steady-state mixing.

Additives: N-octane and Water

The addition of n-octane has improved the efficiency of NO removal. Figure 4 shows efficiency improvements with 0, 1850 ppmv of n-octane. N-octane is similar to gasoline and has a flammability limit of 8000 ppmv at room temperature. The addition of n-octane, suggested by R. Atkinson,¹ uses a process that effectively burns organics by recycling the OH radical. This process should be possible with many organic compounds. It seems likely that the work by Fujii,² using an oil that is vaporized in the processing chamber, is a similar process.

Tests to date have been with dry air and with approximately one percent water. The tests with dry air have an efficiency similar to wet air. We plan tests in the near future with water up to eight percent by volume at 200 °F.

Diagnostics

Diagnostic systems have been used to analyze the light emissions of the discharge. These include a monochromator and an open shutter camera. Devices to measure the results of chemical reac-

Figure 3. Nitric oxide removal. Plots show data from NO and NO_x processing.

Figure 4. Results from *n*-octane addition in NO removal.

tions include a chemical NO_x meter, a chemiluminescence NO_x meter, and an IR and FTIR analyzer.

The measurement of energy is essential to determine the efficiency. We measure the energy by recording the voltage and current as a function of time, and then integrate the product. This gives us the joules per pulse. The pulse rate is measured by a counter. The total energy in any time period is then the product of the time pulse rate and joules per pulse. To prevent reflections, a load resistor is included at the end of a short transmission line, where the voltage is measured with a voltage divider. The current is measured with a 0.1-Ω resistor in the return path.

Applications

Diesel Application. The application of this technology to diesel exhaust cleanup poses many challenges due to weight, size, life, cost, and efficiency requirements. We are developing power supplies with similar requirements as part of the Laser Isotope Separation Program at Lawrence Livermore National Laboratory. It may be possible to

meet these requirements if the efficiency of NO_x removal is sufficiently improved. Our goal would be to remove the required NO_x with less than two percent of the engine power output. This would require 8 hp or 6 kW for a 400 hp engine.

The efficiency of the overall process is the key to diesel applications. The higher the efficiency, the more likely this process will be practical. It may be that the electrical energy can be generated by thermal-electric generators that use the engine waste heat. These devices would require no loss in engine power to clean the exhaust.

Other pollutants may be removed or destroyed by this plasma process. It is likely that fuel droplets, carbon monoxide, and volatile organic hydrocarbons may be oxidized to harmless compounds. It may also be possible to remove particulates using this process in the presence of liquid droplets.

Coal-Fired Power Plants. This technology can be applied to coal-fired power plants. It may be possible to simultaneously remove NO_x, SO_x, mercury, and particulates from the effluent. The removal of both NO₂ and SO_x would be accomplished by their reaction with ammonia. This reaction gives ammonium sulfate and nitrate, which can be sold as fertilizer.

The critical issue in this application is cost. It must be competitive with other processes. Improvement of efficiency results in reduced capital costs and operating costs. Our primary goal is improvement of the efficiency of simultaneous removal of NO_x and SO_x.

Other Applications. There are many applications for pulsed plasma processing. These include destruction of volatile organic hydrocarbons, elimination of hydrogen sulfide from fuel gases, and others where plasmas can induce or accelerate a chemical reaction.

1. Roger Atkinson, *Chem. Rev.* **85**, 69 (1985).
2. K. Fujii, 19th Int. Conf. Phenomena in Ionized Gases (Il Ciocco, Italy), 1991. □

Ground Penetrating Imaging Radar for Bridge Inspection

**John P. Warhus, Scott D. Nelson,
and Jose M. Hernandez**

*Defense Sciences Engineering Division
Electronics Engineering*

Hua Lee and Brett Douglass

*Electronic and Computer
Engineering Department
University of California Santa Barbara*

Erik M. Johansson

*Laser Engineering Division
Electronics Engineering*

We have developed conceptual designs, completed requirements analyses, and performed experiments, modeling, and image reconstructions to study the feasibility of improving ground-penetrating imaging radar technology for efficient and reliable nondestructive evaluation of bridges and other high-value concrete structures. In our feasibility study, we made experimental measurements of frequency-dependent electrical properties of cement, from which we derived an electromagnetic (EM) model for concrete, to use in system-level simulations. We performed parameter studies to evaluate key system design issues, using two- and three-dimensional, finite-difference, time-domain EM analysis codes to simulate an ultra-wideband synthetic aperture radar and produce simulated radar data for a variety of concrete structures. Images produced from simulated radar data were analyzed to evaluate important radar system performance parameters and characterize imaging algorithms we are developing.

Introduction

Ground-penetrating imaging radar (GPIR) radiates very-short-baseband (i.e., without a high frequency carrier) electromagnetic (EM) pulses into ground media such as soil and concrete to probe for features of interest, without disturbing the media. This technology is attractive for use as a bridge inspection tool because it is non-contacting and can produce high-resolution reconstructed images of imbedded structural features using a vehicle moving at highway speeds. However, the full capability of the technology has not been exploited at a commercial level. Limitations preventing current ground-penetrating radar (GPR) systems from being more widely used for bridge inspection include difficult data interpretation (no image reconstruction); inaccurate depth and position measurement; relatively poor spatial resolution; and limited area coverage, which limits operating efficiency.

In an improved bridge inspection GPR system, a mobile ultra-wideband (UWB) radar gathers data for high-resolution image reconstruction of features and defects embedded within the structure. Performance enhancements are achieved by increasing transmitted pulse bandwidth and power, using receiving antenna arrays and synthetic aperture radar processing techniques, and adding high-resolution imaging.

An advanced GPIR and imaging system has the near-term (2- to 4-year) potential of addressing critical national and international needs for reliable, cost-effective nondestructive evaluation of bridges and other reinforced concrete structures. There are more than 578,000 highway bridges in the U.S., and more than 40% of them are either structurally deficient or functionally obsolete.¹ These conditions limit usefulness and can pose a safety threat to the bridge users if the bridges are not properly monitored and maintained.

Figure 1. GPIR bridge inspection concept.

The bridge deck and its wearing surface are the most vulnerable parts of any bridge, undergoing damage from routine service. They are particularly well suited for inspection using a vehicle-mounted inspection system. The deck has a shorter average service life (35 years) than the bridge itself (68 years). The wearing surface, which provides the driving surface and protects the deck beneath it, is usually designed to be replaced many times over the life of the bridge. Concrete slabs with concrete or asphalt cover are the most widely used decks and wearing surfaces in all types of bridge construction.²

Our approach in this study has been to use system-level design, supported by experiments and analytical modeling, to evaluate key system performance parameters and requirements and to determine feasibility.

Progress

During FY-92, our efforts were aimed at defining requirements for improving GPIR performance and evaluating the capability of available technologies to satisfy those requirements. We developed an overall system design concept for an improved inspection system and analyzed its requirements. We investigated the electrical properties of cement (a key constituent of concrete) to develop a model for concrete and to gain insight into imaging enhancement and correction issues. We modeled radar systems and concrete target structures to simulate and evaluate interactions of UWB pulses with clutter sources (aggregate in the concrete, concrete surface reflections, antenna cross-cou-

pling) and targets (structural features like reinforcing bars, or flaws like voids or delaminations). Using analytical capabilities that were improved during FY-92, we also conducted parametric studies to evaluate imaging resolution and performance issues, especially with respect to dispersion effects.

Our FY-92 work showed that current technologies can provide the performance required to implement an improved GPIR with some limited needs for technology development. Additional development work is required in image reconstruction and enhancement, UWB antennas and arrays, and low-power, high-repetition-rate UWB transmitters. Our assessment of these developmental needs indicates a high probability of success in achieving project goals.

System-Level Requirements Analysis

To establish a design baseline for our feasibility study, we formed a basic system-operational concept from which a system conceptual design was developed and performance requirements were defined. Basic operational concept guidelines included: (1) the inspection vehicle moves over the bridge deck at a speed of at least 30 mph; (2) data is acquired for one traffic lane-width of bridge deck with each pass of the vehicle; (3) bridge deck structures are inspected to a depth of 0.5 m; (4) images are reconstructed in three dimensions, with resolution on the order of 50 mm; and (5) image reconstruction is done off-line, at rates permitting 10 to 20 bridges to be covered per day.

As shown in Fig. 1, a transmitting antenna and a linear array of receivers travel over the bridge

Figure 2. Improved GPIR block diagram.

deck surface, sweeping out a traffic lane-wide synthetic aperture. Data recorded from the receivers is transferred via multiple data streams to a mass data storage subsystem, from which it can be accessed for image reconstruction. Image processors in the vehicle or at centrally located processing centers, reconstruct three-dimensional (3-D) images of the bridge deck structure for evaluation by a bridge inspector. Images for a bridge 100 m long and four lanes wide are reconstructed in less than an hour.

Mobile data acquisition, at speeds approaching highway speed limits, will permit efficient and cost-effective evaluation of large areas of bridge decks in very short times. Evaluation of reconstructed images produced from the radar data will allow bridge inspectors to determine bridge conditions, and prioritize maintenance and repair activities and expenditures on the basis of high-quality inspection data.

A more detailed system-level concept is illustrated in block diagram form in **Fig. 2**. Key system requirements that we identified and defined for this design include: receiver dynamic range and minimum discernible signal; the number of receiving channels (and array elements) required to achieve the desired traffic lane-width coverage and image resolution; peak and average transmitter power; transmitted waveform characteristics; transmitting antenna characteristics and pulse repetition frequency; data acquisition and transfer

rates; and computational power required to provide efficient image reconstruction turn-around.

Material Characterization

To better understand the problem of collecting radar data and producing images of features embedded in a lossy heterogeneous material like concrete, we performed broadband (0.1 to 4 GHz) S-parameter measurements of transmission (attenuation) and reflectivity of cement samples. These measurements were made with a network analyzer and a coaxial line in which the dielectric material surrounding the center conductor was formed from cement. From the S-parameter data, we calculated the complex dielectric constant. Many measurements were made over a period of about nine months to observe variations of these properties as the cement cured.

Figure 3 shows typical results of measurements and calculations for a cement sample at eight and 204 days after it was poured. The decreases in relative dielectric constant (ϵ_r) and attenuation over time reflect the reduction of the amount of free water within the curing cement. Important consequences of the frequency dependence of ϵ_r and attenuation are that concrete is dispersive and acts as a bandpass filter. Dispersion distorts the propagating and scattered EM waves in the media by reducing risetime and increasing pulse width, and attenuation reduces the effective bandwidth of the

Figure 3.
(a) Measured transmission (S_{21}) and reflection (S_{11}), and
(b) calculated relative dielectric constant (ϵ_r) for cement sample.

Figure 4. Results from (a) 1-D experimental data and (b) 1-D cement model.

EM energy. These effects degrade the resolution of images reconstructed from the UWB radar data and cause errors in depth measurement.

Data obtained from these measurements were useful in defining the dominant electrical param-

eters of concrete required for accurate modeling using analytical codes like AMOS or TSAR. In addition, knowledge gained from these measurements provided insights into ways in which correction and enhancement of radar data can be achieved.

Modeling and Image Reconstruction

A key element in our studies of system performance requirements was EM modeling of radar system components and targets. Our modeling requirements included needs for one-, two-, and three-dimensional simulations. Those requirements covered a variety of issues important to our feasibility study, including: developing and validating an EM model for concrete; modeling complex bridge-like structures to support our image reconstruction algorithm development effort by providing a means to evaluate algorithm performance; and performing trade studies that examined radar system configuration options and performance parameters.

To satisfy our requirements, we used two finite-difference time-domain EM analysis codes, which were developed and are maintained by Lawrence Livermore National Laboratory. Those codes, AMOS and TSAR, permitted us to evaluate a wide range of technical issues, without requiring the investment of limited project resources to produce physical hardware or execute numerous experiments. In support of our need to model a dispersive material, both codes were upgraded to permit modeling EM wave propagation and scattering in a medium whose dielectric properties are frequency dependent.

By combining results from early material characterization experiments with analytical modeling tools, we developed an EM model for concrete. Permittivity data derived from material characterization measurements were used in a one-dimensional (1-D) model to simulate those measurements. Figure 4 is a plot of measured data overlaid with results from the 1-D model, showing good agreement between measurements and the model.

To extend these results to two dimensions, an additional experiment was performed. UWB pulses were launched through a concrete block, using a broadband antenna, and detected and recorded on the other side of the block with a UWB sensor and recording system. A two-dimensional (2-D) model of the experiment was constructed and run using AMOS. The model used the complex permittivity data from the 1-D case, and included

such details as the antenna beamwidth, radiated electric field waveform, dimensions of the block, dispersive effects of the cement, and clutter effects produced by the aggregate within it. **Figure 5** shows plots of both the experimental measurements and simulated results. Again, fairly good agreement between experiment and simulation provided validation of the concrete EM model.

After confirming the validity of our 2-D EM model for concrete, this analytical tool was used extensively to evaluate radar system design parameters and image reconstruction algorithm performance. Parametric studies we conducted using this model are summarized in **Table 1**. Image reconstructions were made from the simulated radar data for most of the cases listed in the table. The images aided assessments of the impacts of design parameter changes on overall system performance and complexity, and in evaluating image quality for specific imaging techniques. In addition to the studies listed in the table, 2-D simulations permitting evaluation of air/concrete boundary and antenna cross-coupling effects, and of the impact of using multiple transmitters as well as multiple receivers were also run. These studies helped to confirm conceptual design conclusions and permitted us to consider other more complex system configurations.

An example of results from one important study is shown in **Fig. 6**. A series of simulations was run in which a single target of fixed size was embedded at increasing depths within the concrete. The purpose of this series was to evaluate imaged range and cross-range resolution of the reconstructed target and to assess the accuracy of the position location of the target after corrections for dispersion effects had been made. The image sequence was reconstructed using a multi-frequency holographic method, which includes a correction for the effects of dispersion.

Table 1. Model-based parametric studies.

Parameter	Variations
Radiated pulsewidth	100 to 1000 ps
Array element spacing, spatial sample rate	5 to 45 mm
Target cross-section size	5 to 75 mm
Target depth	10 to 150 mm
Clutter source (aggregate) density	10 to 50%
Target density/type	No targets, 1 void, 2 reinforcing bars (rebars), 2 rebars plus 1 void, a rebar grate, and rebar shaded from EM radiation by other rebars

The degrading effects of dispersion and frequency-selective filtering on resolution are clearly shown in these images. As predicted from material characterization measurements and analysis, while the target's dimensions remain fixed, its image increases in size in both down-range and cross-range directions as its depth increases. However, careful analysis of the images shows that the target depth, as indicated by the peak of the image intensity, is located quite accurately when dispersion corrections are applied. The only exception is the case very close (10 mm) to the transmitter and receiving array. The most likely cause for the error, in that case, was EM wave interference that occurred because the reflected pulse from the target was incident on the receiving antennas, while the tail of the transmitted pulse was still propagating past the receivers.

The three-dimensional (3-D) EM modeling effort was started late in the year, to support testing

Figure 5. Results from (a) 2-D experimental data and (b) 2-D concrete model.

Figure 6. 2-D image sequence of rebar target at increasing depths.

Figure 7.
(a) Physical model of four rebars in free space and
(b) volumetric rendering of 3-D image reconstruction.

of 3-D image reconstruction software. Very simple physical models were used in the early tests. An example of a test case is shown in **Fig. 7**, in which four rebars, three of which have gaps, are assembled in free space. This simple model permitted evaluation of the imaging software without including the complicating effects of clutter, dispersion, and filtering. After the image was reconstructed, it was processed and enhanced with some rudimentary techniques to provide a means for viewing the 3-D rendering as shown in the figure.

Images of the rebars are clearly visible in the rendering; however, the gaps in the bars are not. The gaps are not seen in the rendering because they did not produce any reflection of the EM energy launched in the simulation, and the energy scattered from the rebars tends to fill in the voids. In the case where air-filled gaps in rebars are embedded in concrete, we do expect to detect and image the gaps because the air/concrete interface at the gap will produce a significant phase reversed reflection.

Future Work

Our continuing efforts are aimed toward a field demonstration of a limited-capability prototype system late in the next fiscal year. To support that effort, we will complete a series of experiments to confirm key modeling results and verify system design parameters. Those experiments will be conducted using a concrete test slab that was designed

to simulate bridge construction features, and in which we embedded several flaw simulants. UWB antenna and transmitter development will be pursued, and image reconstruction algorithm development, testing, and refinement will continue with the goal of having optimized radar hardware and imaging code available late in the year to support the demonstration. A low-cost prototype system will be designed to permit demonstration of base data acquisition and image reconstruction performance. The objective of the demonstration will be to show improved performance in resolution, and accurate reconstruction of embedded structure.

Acknowledgements

We wish to thank Jim Brase, Remote Sensing, Imaging, and Signal Engineering Thrust Area Leader, and John DeFord, Computational Electronics and Electromagnetics Thrust Area Leader, for their support in supplying the resources needed to develop and evaluate imaging techniques, to perform EM modeling, and to enhance the capabilities of EM modeling codes for this project.

1. *Our Nation's Highways: Selected Facts and Figures*, U.S. Department of Transportation, Federal Highway Administration, Publ. No. FHWA-PL-90-024.
2. N.P. Jones and B.R. Ellingwood, "NDE of Concrete Bridges: Opportunities and Research Needs," Federal Highway Administration Conf. on NDE for Bridges (Arlington, Virginia), (August 25-27, 1992). □

High-Average-Power, Electron Beam-Controlled Switching in Diamond

W. Wayne Hofer

*Defense Sciences Engineering Division
Electronics Engineering*

**Karl H. Schoenbach,
Ravindra Joshi, and
Ralf P. Brinkmann**

*Old Dominion University
Norfolk, Virginia*

Don R. Kanla

*Inertial Confinement Fusion Program
Laser Programs*

The superior electronic and thermal properties of diamond make it an ideal material for a high power solid-state switch. Our FY-92 goals were to identify and address technical issues that could potentially limit the anticipated performance of electron beam-triggered, high power switching in diamond. In particular, we concentrated on the role of contacts and non-linear effects at high electric fields, electron beam range in diamond, and carrier transport modeling.

Introduction

The superior electronic and thermal properties of diamond make it an ideal material for a high power solid-state switch. We predict that an electron beam-controlled diamond device could switch well over 100 kW average power, at megahertz repetition rates, with greater than 95% efficiency and voltages greater than 5 kV.

High power diamond switches could significantly increase the performance of high power-switched power supplies, modulators, and power converters. Commercial applications include high power radar, control for electric vehicles, high power industrial controllers, and possibly solid-state switching at utility substations.

The crystal structure of diamond is relatively well characterized. It is a semiconductor with a band-gap of 5.5 eV at 300K. By comparison, the band-gap of GaAs is 1.4 eV. The high band-gap of diamond results in a small dark current compared to Si or GaAs. As a result, the breakdown field or holding voltage is very high, i.e., 1–10 MV/cm. The electron and hole mobility are approximately

2000 cm²/Vs. At room temperature, diamond has the highest thermal conductivity of any solid, 20 W/K cm, about five times that of copper. The electronic properties of chemical vapor deposition (CVD) diamond now exceed those of the best natural diamond (Table 1). CVD diamond substrates can be cooled using microchannel cooling, a highly efficient thermal management technology developed at Lawrence Livermore National Laboratory (LLNL). When the electronic proper-

Figure 1. Electron beam-controlled switch. In our switch, 100 keV electrons are absorbed in a thin diamond film, and by ionization, generate a high concentration of electric carriers in the diamond.

Table 1. Electronic properties of diamonds.

	Microwave films	Single-crystal natural II-A	Homoepitaxial film
Thickness	25–500 μm	$1 \times 1 \times 3 \text{ mm}^3$	120 μm
Grain size	10–100's μm	single-crystal	single-crystal
Electrical resistivity ($\Omega\text{-cm}$)	$10^5\text{--}10^{11}$	$> 10^{11}$	$> 10^{11}$
Lifetime (ps)	100–800	100–1000	150
Mobility (cm^2/Vs)	500–4000	2800	3000
Raman	1330–1334 FWHM 4–9/cm	1332.4 peak (FWHM 2.4/cm)	1332/cm peak (FWHM 2.9/cm)

ties of diamond and its superior thermal properties are combined with microchannel cooling and the rapid advance in CVD technology, diamond becomes an excellent solid-state material for advanced, high performance power electronics.

Progress

In our switch (Fig. 1), a high concentration of carriers (corresponding to kA/s/cm^2) are created by ionization when a high voltage, low current

electron beam is absorbed in the diamond film. The controlling electron beam can be generated and modulated at megahertz frequencies by compact, long-life, commercially available grid-controlled thermionic cathodes. As an alternate to thermionic cathodes, recent research and development of new high-current-density electron sources, such as ferroelectric cathodes, micro-field emission cathodes, and even diamond field emission cathodes, could potentially be combined with a thin film diamond to create a very compact, robust, high power solid-state diamond switch.

Our FY-92 goals were to identify and address technical issues that could potentially limit the anticipated performance of electron beam-triggered, high power switching in diamond. In particular, we concentrated on the role of contacts and nonlinear effects at high electric fields, electron beam range in diamond, and carrier transport modeling. Our work is a combined effort with researchers at Old Dominion University at Norfolk, Virginia, and at LLNL.

Contacts and Nonlinear Effects

Diamond is normally thought to be an excellent high voltage insulator. However, we have shown that for both natural and CVD diamond on silicon, the dark current (no electron beam-generated carriers) increases by 10–11 orders of magnitude at high electric fields.

For natural II-A diamond, the strong nonlinear increase starts at 200-kV/cm for 35 μm -thick diamond (Fig. 2) and at 400-kV/cm for 50 μm -thick diamond. We believe that this threshold corre-

Figure 2. Dark current vs applied voltage for 35- μm natural II-A diamond film. The current increases rapidly once the trap-filled limit is reached ($\sim 200 \text{ kV/cm}$). Similar results were obtained for 50- μm -thick diamond, but the dark current increased rapidly at about 400 kV/cm.

Figure 3. Drift-diffusion modeling results. A model based on charge injection qualitatively predicts the rapid increase in current at high electric fields.

sponds to the trap-filled limit. The thickness dependence correlates well with photoelectronic theory where the trap-filled-limit electric field is proportional to the square of the material thickness. As the field is further increased, dark current is dominated by charge injection at the contacts. Both our qualitative and more comprehensive drift-diffusion modeling results (Figs. 3 and 4) predict these results. At even higher fields, a negative differential resistivity phase quickly leads to de-

Figure 4. Drift-diffusion modeling results. Data from our drift-diffusion model with injecting contact and deep trap centers agree with the behavior observed qualitatively and experimentally.

Figure 5. Dark current vs voltage for 1-μm-thick CVD diamond on n-silicon. The onset of rapidly increasing dark current depends on the polarity of the bias. When the silicon is biased negative, the hold-off voltage is highest.

struction of the switch, most likely due to current filaments.

Similar to natural diamond, the dark current in CVD diamond on a heavily doped ($\sim 10^{18} \text{ cm}^{-3}$) n-silicon increases rapidly at high fields (Fig. 5). However, the electric field threshold was in excess of 0.9 MV/cm, much higher than that for natural diamond, and it depends strongly on the bias polarity. Apparently silicon is a very

Figure 6. Voltage vs time for electron beam-switched, 35-μm-thick, natural II-A diamond at two different bias levels. At the lower field (a), the conductivity follows the electron beam, but at the higher field (b), the current continues after the beam is turned off, due to charge injection.

Figure 7. Electron beam-induced conductivity in 1- μm -thick CVD diamond on n-silicon for opposite polarities. When the n-silicon is negative (a), the switch conductivity follows the beam current. However, when the n-silicon is positive (b), the switch conductivity persists after the beam is turned off.

good blocking contact.

Dark current in diamond is highly dependent on carrier recombination and trapping at deep energy levels in the diamond and whether contacts are blocking or injecting.

Electron Beam-Induced Conductivity

When the natural diamond switch is irradiated with an electron beam, the switch conductivity follows the beam profile at lower electric fields; but at higher fields, the switch remains conducting when the beam is turned off (Fig. 6). At even higher fields, the switch failure is likely due to filamentary current. We believe this corresponds to operation in the negative differential resistivity mode.

When irradiated with an electron beam, the conductivity of the CVD diamond follows the beam profile (Fig. 7) up to 1.8 MV/cm when the silicon is biased negative. However, when the silicon is biased positive, the CVD diamond remains

Figure 8. (a) Monte-Carlo calculations of 150-keV electron beam penetration in 35- μm diamond. Scattering effects in a 25- μm Ti anode foil are included. (b) Transmission of the electron beam in a 35- μm -thick natural diamond film. The electrons are completely absorbed at about 130 keV.

conducting even when the beam is turned off.

Based on these data, it appears that CVD diamond on silicon may limit carrier injection, thus enabling us to switch higher voltages.

Based on our current data, we should be able to switch voltages ranging from 400 to 4000 V. If the lock-on field can be extended 5–10 times by tailoring the diamond growth and contacts, we may be able to produce an on-off switch operating at 20 to 40 kV.

To hold-off and switch higher voltages, we must extend the onset voltage threshold of the rapidly increasing dark current by using better blocking contacts.

Electron Penetration Depth

Electron penetration depth determines the maximum diamond thickness for a given electron beam energy. The diamond thickness in turn determines the maximum hold-off voltage.

Modeling results show that the penetration depth for 150 kV electrons in diamond is about

35 μm (Fig. 8a). These results are confirmed by our experimental data (Fig. 8b).

Future Work

To switch the highest possible voltage and power, we must extend the electric field threshold of the nonlinear increase in dark current. This will be accomplished with non-injecting contacts (blocking contacts) and by understanding and controlling deep-trap center impurities in the diamond switch. We will concentrate our efforts on CVD diamond grown on highly doped silicon and determine how voltage hold-off scales with diamond thickness.

We will obtain data on deep-center impurities and defects in diamond by using Electron Beam-Induced Current Transient Spectroscopy (EBICTS). EBICTS spatially resolves the activation energy and density of deep-level traps. These data will be used in our drift-diffusion models that calculate carrier transport in diamond at high electric fields.

Finally, we will construct a prototype switch to demonstrate kilovolts switching in diamond and a range of hundreds of amperes.

1. R.H. Bube, *Photoelectric Properties of Semiconductors*, Cambridge University Press (Cambridge, England), 1992.

Testing of CFC Replacement Fluids for Arc-Induced Toxic By-Products

W. Ray Cravey

*Defense Sciences Engineering Division
Electronics Engineering*

**Ruth A. Hawley-Fedder and
Linda Foiles**

*Condensed Matter and Analytical
Sciences Division
Chemistry and Materials Science Department*

Wayne R. Luedtka

*Computer and Communication
Engineering Division
Electronics Engineering*

We have developed a unique test-stand for quantifying the generation of perfluoroisobutylene (PFIB) in chlorofluorocarbon (CFC) replacement fluids when they are subjected to high electrical stress/breakdown environments. PFIB is an extremely toxic gas with a threshold limit value of 10 ppbv as set by the American Conference of Governmental Industrial Hygienists. We have tested several new fluids from various manufacturers for their potential to generate PFIB. Our goal is to determine breakdown characteristics and quantify toxic by-products of these replacement fluids to determine a safe, usable alternative for present CFC's. We are currently working with 3M, DuPont, and Ausimont, key manufacturers of these replacement fluids, to test them for potential PFIB generation.

Introduction

Restrictions on the use of chlorofluorocarbons (CFC's) worldwide, nationally, and at Lawrence Livermore National Laboratory (LLNL) will have an enormous impact on industry and government laboratories. On September 16, 1987, several CFC-producing nations including the United States signed the Montreal Protocol, which called for the phase-out of production of CFC's no later than the year 1997. President Bush, reacting to scientific data showing the imminent danger of an ozone hole over the Northern Hemisphere, ordered the phase-out of CFC's by the year 1995, two years early than the Montreal protocol.¹ Worldwide usage of CFC is estimated at 750,000 metric tons² (see Fig. 1). Almost half of this amount is used either as cleaning agents in electronic PC board manufacturing (24%), or in the foam blowing industry (another 24%). The majority of the remaining CFC use is in refrigeration and aerosol sprays. CFC's are used extensively in the automobile

industry, as well, as a refrigerant for vehicle air conditioners. Although several replacements for existing CFC's do exist, many of these replace-

Figure 1. Worldwide use of CFC. Total use is 750,000 metric tons.

Figure 2. Block diagram of CFC replacement fluid test-stand. The user sets the time or number of pulses for the desired test: AC, DC, or pulse. The output of the corresponding generator is fed through a matching network into the dielectric test cup. The test cup houses the gap electrodes and contains the fluid under test. Samples are removed from the test cup and analyzed on a gas chromatograph (GC) or GC mass spectrometer, to quantify the amount of PFIB that was produced, if any. The voltage across the gap and the coinciding current are digitized and recorded on a computer. There they are analyzed, and the power and energy are determined.

Figure 3. Photo of test-stand.

ments are toxic,³ flammable, or highly expensive. In addition, two replacements, although not toxic, have been identified as ozone depletion agents, and their use will be phased out in the near future.¹

We are studying several new replacement fluids for CFC's that would have similar electrical and thermal characteristics. CFC's are currently used as high voltage electrical insulators and dielectric coolants for the high-average-power modulators used to drive the copper vapor lasers at the Atomic Vapor Laser Isotope Separation (AVLIS) facility at LLNL. Several substitutes have been suggested to replace these fluids. But a stumbling block associated with these replacements is the potential to generate toxic gases, such as PFIB, when the fluids are subjected to high electrical stresses and/or breakdowns.

Progress

Over the last year, we designed, fabricated, and tested the new CFC replacement fluid test-stand,

which was our foremost goal. Work is proceeding on the compressive data collection and analysis that is necessary to quantify the toxic by-product production for given breakdown conditions. Initial results from tests conducted with the test-stand show a linear trend with respect to arc energy. We have received funding from the Superconducting Super Collider (SSC) for analysis and testing of the cooling fluid used in their low-energy booster (LEB) cavities. A more descriptive summary of our progress is given in the subsequent sections.

Replacement Fluid Test-Stand

We have identified three electrical breakdown/stress environments that may contribute to PFIB production in CFC replacement candidates: AC breakdown; high DC field stress; and pulsed breakdown. Our test-stand was designed to simulate all three of these environments. A block diagram and description of the operation of the test-stand are given in Fig. 2; Fig. 3 is a photograph of the test-stand.

An important test that has application in the refrigeration industry is breakdown due to high AC voltages. We have the capability of producing 60-Hz AC, high voltage breakdown conditions with voltages ranging from 0 to 40 kV, and any desired gap spacing across the test cell electrodes. Our capabilities allow us to simulate the inside environment of the ordinary refrigeration compressor/motor assembly.

High DC field stress occurs in many situations where there are high voltages present. Electrical arcing is not associated with these conditions; however, there can be extremely high fields and corona onset. With our system, we are able to generate these high pre-breakdown fields in the fluid-under-test for any preset time limit. After the given time limit, the fluid is analyzed for PFIB formation.

Pulsed breakdown environments are produced with many high voltage modulators. Typically, these modulators are used for driving radars, lasers, and accelerator cells. We have a wide range of pulsed conditions that can be produced with our present test-stand. In addition to being able to produce the pulsed conditions mentioned, we have implemented a complete electrical diagnostic system for measuring the breakdown voltage, discharge current, arc power, and energy that are associated with each pulse. Through the use of the data that is recorded by the diagnostics, we are able to correlate the quantity of PFIB produced with the pertinent control variables, such as voltage, current, pulse-width, pulse repetition frequency (prf), and energy.

Experimental Results

Measurements have been made on a candidate replacement fluid for the copper vapor laser modulators. The fluid was subjected to a 30-kV pulse at a pulse repetition rate of 75 Hz, with a full-width half-maximum of 100 μ s. A 10-mil gap spacing with brass electrodes conforming to ASTM standards⁵ was used for testing. The dielectric test cup was filled with 85 ml of the fluid under test. Samples were taken from the dielectric test cup before exciting the fluid, at 20 kV, 40 kV, and 100 kV pulses. Between each sample interval, the voltage and current waveforms were recorded, and the instantaneous power and energy were calculated for the arc. A typical data set is illustrated in Fig. 4.

There are two loss mechanisms associated with the arc discharge: resistive/inductive phase⁶ losses and conduction loss. The resistive/inductive phase losses are produced during the time the voltage collapses across the gap and the current begins to rise. During this phase, there is a power and energy loss associated with the instantaneous current rise and voltage collapse. The faster the voltage collapses, the less appreciable these losses are. The second loss mechanism, which appears to be the most dominant in this experiment, is the loss associated with the voltage drop across the arc itself. The forward drop of the spark gap was observed to jump between 40 and 60 volts. The maximum output current is 1 amp for the present configuration, limited by the output transformer.

The samples were analyzed on a dual column gas chromatograph equipped with an electron capture detector. Results from the analysis are shown in Fig. 5. The reduced data shows a clear trend with respect to energy. We would like to predict the amount of PFIB that is formed for higher energies, by using the data we collect on the test-stand. Initial data looks promis-

Figure 4. Typical data for (a) voltage and (b) current waveforms.

Figure 5. Typical data set for pulse breakdown-induced PFIB generation. The fluid sample was pulsed with a 30-kV, 1- μ s pulse at a prf of 75 Hz. This data was generated with brass electrodes and a 10-mil gap spacing in the dielectric test cup. The energy per pulse is 4 mJ.

ing. The calculated field for the breakdown voltage is much lower than what was expected based on the published fluid characteristics. Further investigation showed that the breakdown level is much higher at lower prf due to fluid recovery. Although this is no surprise, it is a key variable in the pulsed breakdown of these fluids.

Superconducting Super Collider Tests

We have been funded by the SSC to test for the amount of PFIB that is potentially produced in their LEB cavities. We have set up a working agreement with SSC to establish PFIB generation data for LEB cavities. Also, we are providing measurement capabilities for quantifying

PFIB in samples they provide. The first sample generated by SSC was subjected to 60 kV for 20 hours of operation. An electrostatic model of the LEB cavity was generated using Ansoft's Maxwell 2D7, and the maximum electric field in the fluid was calculated to be 83 kV/cm. They reported that during the operation, there were no detectable breakdowns. The samples were analyzed, and no PFIB was measured above the 60 ppbv detection limit.

Future Work

Our plans for the next fiscal year are focused on three key areas.

- (1) We are currently working to generate a comprehensive and complete data set for various arc-induced breakdown conditions for various fluids. The last year was dedicated to developing the needed test-stand and diagnostics as well as chemical and analytical techniques. Now that the testing facility is in place, we will fill in our data set and analyze the results for PFIB generation trends, with respect to parameters such as energy, power, and prf.
- (2) In addition to the continued testing of the replacement fluids, we propose to test, in cooperation with 3M, a fluid contamination detection system. The system uses a UV source (not specified) and detector to measure the transparency of the fluid. Initial tests have been conducted by 3M, which show that the fluid's transmission changes by as much as 20% when the fluid is subjected to high thermal stress. We will test various detector configuration and breakdown parameters to decide if the detector can be

used as a reliable means to signal the possibility of PFIB contamination in hostile working environments.

- (3) The third area that has been identified is the refrigeration industry. In the majority of industrial refrigeration systems, the refrigerant is circulated through the compressor motor, for cooling and lubrication.⁸ In large systems, the voltage level can exceed 1000 volts, leading to the occasional and often catastrophic electrical breakdown of the fluid. Our test-stand is capable of reproducing these breakdown conditions in the laboratory where a comprehensive analysis can be performed.

1. Statement by Presidential Press Secretary Fitzwater on the Phaseout of Ozone Depleting Substances, February 11, 1992.
2. P. Elmer-Dewitt, "How Do You Patch a Hole in the Sky That Could Be as Big as Alaska?," *Time* 139 (7), (February 17, 1992).
3. A.K. Naj, "CFC Substitutes Might Be Toxic, Rat Study Finds," *Wall Street Journal*, July 2, 1991.
4. M. Weisskopf, "Study Finds CFC Alternatives More Damaging Than Believed," *The Washington Post*, February 23, 1992.
5. ASTM Standard D 877-87, *Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes* (1989).
6. J.C. Martin, *Nanosecond Pulse Techniques*, Atomic Weapons Research Establishment, United Kingdom Note 4, 1970.
7. *Maxwell 2D Field Simulator*, Version 4.33, Ansoft Corporation.
8. Althouse, Turnquist, and Bracciano, *Modern Refrigeration and Air Conditioning*, The Goodheart-Willcox Company, Inc., (South Holland, Illinois) 1988. □

Applying Statistical Electromagnetic Theory to Mode Stirred Chamber Measurements

**Richard A. Zacharias and
Carlos A. Avalle**

*Defense Sciences Engineering Division
Electronics Engineering*

We are developing measurement and analysis tools to assess microwave effects on electronic subsystems that operate in large metal cavities, such as avionics boxes in aircraft. The measurement tool is the mode stirred chamber (MSC), which is a metal-walled chamber, large relative to a wavelength, into which electromagnetic energy is injected. It usually contains a stirrer paddle to randomly change resonant mode patterns as a function of time. The analysis tools are based on statistical electromagnetics. This theory predicts that the microwave power measured at an arbitrary point (not near the walls) within an overmoded, randomly complex cavity is a Chi-squared distribution with two degrees of freedom. This is a single-parameter distribution. Therefore, the mean power density measured at an arbitrary point in the cavity is sufficient to develop a complete statistical model of the power at any arbitrary interior point. By showing that a randomized aircraft equipment bay has sufficient Q and ensemble variations to behave as such a random complex cavity, we have determined that the mean coupling measured at a point in the cavity would be sufficient to predict the microwave stress (statistical distribution of fields) to which an avionics box would be exposed over an ensemble of like aircraft (the fleet). A MSC could be used to generate the same distribution for testing avionics boxes uninstalled. This method could provide tremendous cost savings in testing. In FY-92, we developed a small, low-power MSC and verified that its interior power distribution is indeed predicted by the theory. We also made measurements in two equipment bays of a Boeing 707 aircraft and verified that the power measured at various points in these cavities has the same distribution. The aircraft tests were funded by the NASA Langley Research Center and were conducted in collaboration with the U.S. Naval Surface Warfare Center, Dahlgren.

Introduction

Modern transportation systems and military systems are increasingly dependent on sophisticated electronic controls. At the same time, the potential for electromagnetic (EM) susceptibility of electronic systems is increasing for several reasons: modern integrated circuits with higher densities and speed are often more sensitive to EM transients; modern composite material structures may provide poorer EM shielding; the EM power in the environment is increasing as more users share the airwaves. Because of these factors, the

need to ensure the survivability of electronic systems that may be exposed to high-power EM signals has become of great interest. Advisory regulation has recently been drafted for aircraft that would require testing and/or analysis to assure the EM hardness of installed flight critical and flight essential equipment. Similar safety assurance certification procedures may be imposed on other electronically controlled transportation systems of the future. The Department of Defense (DOD) is particularly interested in developing methods for assessing potential EM effects on military systems, since the normal environment these

Figure 1. Block diagram of Mode Stirred Chamber instrumentation.

systems operate in is often quite severe (e.g., an aircraft carrier deck), and since these systems may be exposed to high-power signals intentionally transmitted by an adversary. The DOD also needs similar methods to assess the lethality of proposed EM weapons against candidate targets.¹

While full-system, full-threat testing may be the most thorough manner to determine susceptibility, it is often too expensive to be practical for large systems. Computer models alone have been unsuccessful in accurately predicting EM susceptibility, especially at high frequencies. At Lawrence Livermore National Laboratory (LLNL), we have developed economical assessment techniques based on measuring and comparing EM stress and strength.² The power to a device or circuit (stress) is extrapolated from a low-power EM coupling measurement and is compared against the upset threshold (strength) of the device or circuit. A system model is used to relate device or circuit effects to system effects. This technique works well for small systems such as missiles and land mines, but for large systems, the number of measurements and analyses becomes large. In addition, as the system size becomes many wavelengths, the coupling as a function of frequency and angle also becomes extremely complex to the point that deterministic descriptions cannot be made. In this regime, new methods of testing and modeling must be developed. We believe that the mode stirred chamber (MSC) and statistical electromagnetics will provide a new method to make viable stress-vs-strength comparisons for subsystems.^{3,4,5}

Progress

Our first major accomplishment was to develop a small, low-power MSC. The chamber was equipped with a power leveling circuit and with automated control and data acquisition instrumentation. Chamber performance was characterized. Our second major accomplishment was to measure and analyze the statistical distribution of microwave power in equipment bays of a full-sized transport aircraft. The measured distribution matched that measured in the MSC and that predicted by theory.

MSC Development

Our MSC was built from an existing transverse electromagnetic (TEM) cell. A TEM cell is designed to operate single mode and produces a well-known field pattern usually used to calibrate sensors. Above its cutoff frequency, the TEM cell becomes increasingly overmoded. To promote more effective overmoding, we removed a section of the septum (center conductor), and added large reflective diffusers, to scatter the energy in random directions within the cell. A motor-spun stirrer paddle, large compared to the wavelength, randomizes the field pattern as a function of time. At frequencies greater than several times the cutoff ($f > 400$ MHz), the mode density is large, and the stirring produces random field patterns.

Figure 1 shows a block diagram of the MSC instrumentation. A low-power microwave source

delivers the EM energy into the chamber. The rf signal can be fed into the chamber through the usual TEM cell input port or by a separate horn antenna placed inside the chamber. A power leveling unit was developed to dynamically adjust the power to compensate for power reflected at the transmit antenna due to changes in the voltage standing wave ratio (VSWR) as the stirrer turns. We used a variety of sensors and antennas, and a spectrum analyzer to measure power at various points in the chamber. Fully automatic control and data acquisition were implemented with a personal computer.

Boeing 707 Tests

Tests were conducted at Davis Monthan Air Force Base in Tucson, Arizona. The experimental setup is shown in Fig. 2. The interior of the aircraft equipment bay under study was instrumented with two transmit and two receive antennas. Each pair consisted of a long wire and a horn antenna. The transmit antennas were driven by low-power microwave sources installed in an adjacent instrumentation van, and were oriented to avoid direct illumination of the receiving antennas. Spectrum analyzers were used to measure power at various points within the bays, while a motorized stirrer paddle randomly changed the mode pattern as a function of time. The stirrer motion simulated the random variations in the position of equipment in the bays throughout the fleet of aircraft. Portable computers were used for data acquisition and analysis. Power was measured at discrete frequencies for each of the four possible transmit and receive antenna combinations. The measurements were repeated for several antenna locations within the aircraft bays.

Analysis and Results

The time (or stirrer position) waveforms for both the MSC and aircraft data looked similar in that the received amplitude varied rapidly with excursions of 20 dB or more. The time data was statistically analyzed to generate probability density histograms of the power (in dBm). These are shown in Fig. 3 (a and b), for the aircraft and MSC, respectively, along with the theoretical probability density (dashed curves). The predicted density was derived from a two-degree-of-freedom, Chi-squared density using a variable transformation to convert to dB. The aircraft and MSC data compare well to each other and to theory.

Figure 2. Block diagram of instrumentation for microwave power statistical distribution measurements made at Davis Monthan Airbase on a Boeing 707.

Figure 3. Probability density of measured power in (a) the mode stirred chamber and (b) the equipment bay of a Boeing 707.

Future Work

Four issues must be resolved before certified, quantitative subsystem assessments can be made in MSC's:

1. MSC tests must be shown to be repeatable, predictable, and rigorous. This is necessary for the technique to be accepted by government regulators and industry.
2. The power distribution in the MSC must match that found in the system cavity. This ensures that the subsystem sees the same EM power environment as if it were installed.
3. Coherence length must be understood and the effects of structures near the subsystem taken into account. A structure installed in the cavity will interact with a subsystem if their separation is within a coherence length. Therefore, structures within this length will need to be simulated in the MSC for accurate results.
4. The transfer function describing coupling to devices in the subsystem must be shown to be separable into a product of coupling from outside the system cavity to its interior, and coupling from the cavity interior to the devices within the subsystem. An example of a non-separable case is when the major coupling into the subsystem is through a waveguide that exits the cavity. In this case, the random field environment in the cavity is immaterial, and MSC tests would not provide accurate results.

In FY-92, we developed a small MSC facility and instrumentation. We made measurements in the MSC and in a commercial aircraft that showed that the power distributions matched each other and the theory. In FY-93, we are planning experiments to resolve the remaining issues. We will use statistical EM theory to make predictions of the coupling as a function of frequency, onto simple

wire antennas in the MSC, and compare those predictions against measurements. This will help to demonstrate that MSC tests can be rigorous and predictable. Since the prediction will be based on the correlation of the field components picked up by wire segments of the antenna, this will also serve to validate our understanding of coherence length. Separability will be demonstrated experimentally in our anechoic chamber and MSC using simple metal boxes representing an airframe and an avionics box. Once shown for a simple case, the measurements will be repeated with various cable and transmission line connections to the avionics box to establish the cases where separability does and does not hold.

The end product of this study will be a set of theoretically and experimentally validated EM susceptibility assessment tools that would allow accurate EM effects testing of subsystems at high frequency, while avoiding expensive high-power full-system tests.

1. A. Pesta and N. Chesser, *Department of Defense Methodology Guidelines for High Power Microwave (HPM) Susceptibility Assessments*, Office of the Secretary of Defense, HPM Methodology Panel Report, Draft (1989).
2. R. Mensing, R.J. King, and H.S. Cabayan, *A Method for Estimating the Susceptibility of Electronic Systems to HPM*, Lawrence Livermore National Laboratory, Livermore, California, UCID-21430 (1988).
3. M. Crawford and G. Koepke, *Design, Evaluation, and Use of a Reverberation Chamber for Performing Electromagnetic Susceptibility/Vulnerability Measurements*, NBS Technical Note 1092 (1986).
4. R. Price, H. T. Davis, R. H. Bonn, E. P. Wenaas, R. Achenbach, V. Gieri, R. Thomas, J. Alcala, J. Hanson, W. Haynes, C. McCrea, C. Montano, R. Peterson, B. Trautlein, and R. Umber, *Determination of the Statistical Distribution of Electromagnetic Field Amplitudes in Complex Cavities*, Jaycor Report No. 88JAL129 (1988).
5. T. Lehman, *The Statistics of Electromagnetic Fields in Cavities with Complex Shapes*, Phillips Laboratory Interaction Note (1993).

Magnetically Delayed Low-Pressure Gas Discharge Switching

**Stephen E. Sampayan,
Hugh C. Kirbie, and
Anthony N. Payne**

*Laser Engineering Division
Electronics Engineering*

**Eugene Lauer and
Donald Prosnitz**

*Advanced Applications Program
Laser Programs*

We have investigated the properties of a magnetically delayed, low-pressure gas discharge switch. We performed measurements of the closure and recovery properties of the switch; performed quantitative erosion measurements; and observed the onset of x ray production in order to compare switch properties with and without delay. Further, we performed qualitative optical measurements of transition line spectra to correlate our electrical recovery measurements with plasma deionization.

Introduction

Fast-closure-rate, high-voltage (> 100 kV), high-current (> 10 kA), high-repetition-rate (> 1 kHz) switching has remained a major area of research in the pulsed power field.^{1,2,3} Solid-state switching has generally been limited to several tens of kilovolts; high-pressure gas discharge switching is limited to repetition rates below 1 kHz; vacuum switching is generally a slow closure process; and magnetic switching requires extremely precise voltage and reset state control to minimize jitter.

Low-pressure gas discharge switches have shown promise as a fast-closing, high-repetition-rate device such that if sufficiently fast closure times can be achieved, single-stage power conditioning chains would become feasible.^{4,5}

The primary difficulty with this switch, however, is anode electrode damage during closure initiation, resulting in short lifetimes. Once triggered, electrons emitted from the cathode plasma can form a pinched beam and deposit significant enough localized energy to vaporize anode material. Inserting a series delay element, which inhibits the application of full voltage and current until such time that the discharge plasma has filled the gap, minimizes this effect. It is this version of the low-pressure switch that we are presently studying.

Progress

Our magnetically delayed low-pressure switch (MDLPS) test-stand was built primarily to support the long-pulse, relativistic klystron (RK) and free electron laser (FEL) work at Lawrence Livermore National Laboratory (LLNL).⁶ In this application, a closing switch initiates a pulse, which is delivered to an induction accelerator cell.⁷ The induction cell accelerates an injected electron beam to a sufficient energy suitable for the RK or FEL.

Apparatus

The MDLPS test-stand (**Fig. 1**) consists of a single water-filled, 12- Ω , 70-ns Blumlein from the advanced test accelerator at LLNL. The Blumlein is attached to a liquid load and charged from a single dual-resonant transformer. The transformer is powered by two charged capacitor banks discharged through separate thyratrons, diode isolated and fired sequentially to produce two charging pulses. A trigger pulser initiates a single closure event at the peak of the first charging pulse; the second, variable timing, charging pulse is allowed to ring to zero and is used as a test pulse to verify gap recovery.

The low-pressure gas gap consists of an anode-cathode electrode pair separated a sufficient dis-

Figure 1. Switch test-stand used to study magnetically delayed switch properties.

tance to prevent self breakdown (at approximately 100 to 150 kV/cm). A surface flashover triggering device, embedded within the cathode, initiates the ionization processes that render the gas highly conductive. A saturable inductor placed in series with the switch, delays the onset of full current, allowing the ionization processes to spread throughout the gap volume prior to full closure. The saturable inductor is designed to limit current flow below the threshold for constricted discharges, and hold off the full anode-cathode voltage until the discharge has filled the gap volume.

Diagnostics for the test-stand consisted of current and voltage sensors for the switch and Blumlein. Other diagnostics consisted of a fast x-ray detector, a fast gated camera, and a 0.25-m monochromator. At preset, we used an image-intensified gated camera to observe the monochromator output. We are installing a gated photomultiplier system for future work.

Experiments

We performed standard parametric studies of the magnetically delayed low-pressure switch and com-

pared the performance with and without the saturable inductor. A comparison of typical closure properties is shown in Fig. 2, and of typical recovery properties in Fig. 3. For these data, the gap spacing was 1 cm, the gas was nitrogen, and the anode-cathode voltage was 90 kV.

Closure time, defined as the 10 to 90% transition time of the voltage across the low-pressure gas gap, showed a factor-of-two improvement at lower pressures with the magnetic delay, i.e., with the saturable inductor. At higher pressures, above approximately 7 mT, the saturable inductor had little effect.

Recovery time with the series saturable inductor improved significantly and was extremely reliable: 90% recovery probability was estimated. At lower pressures, extremely good recovery times (approximately 50 μ s or 20 kHz-equivalent pulse repetition frequency) were observed, while at higher pressures, recovery time was observed to be 5 μ s. By contrast, recovery probability without the series saturable inductor was not reliable and was measured to be between 80 and 90%. Although at lower pressures and this recovery probability, faster recovery times were observed, recovery did not occur above 7 mT.

We made qualitative spectroscopic measurements of late-time line emission from the gap in order to verify our recovery measurements performed electrically. Spectroscopic observations of the discharge showed that line radiation from the nitrogen decayed within 10 μ s after current cessation. Line radiation characteristic of the anode material, however, required greater than 50 μ s to decay. This result was consistent with our electrical measurements.

Erosion rates with the series saturable inductor were a factor of 60 less than those of a similar lifetime test without the series saturable inductor. Photographic comparisons are shown in Fig. 4. These tests were conducted at 90 kV, with nitrogen at 8 mT pressure and using aluminum anodes. In the first test (Fig. 4a), severe anode damage was observed over the entire surface of the electrode and particularly across from the trigger electrode. The total number of shots was

Figure 2. Measured closure results with and without delay.

Figure 3. Electrically measured recovery results.

approximately 16,000. In the second test (Fig. 4b), a less pronounced indentation resulted from the test, with minimal damage having occurred throughout the anode surface. The total number of shots during this latter test was approximately 400,000.

We performed x ray measurements (Fig. 5) to understand the time evolution of electron emission from the cathode of the low-pressure switch. Our relative measurements of the integrated x ray output during switch closure showed an order-of-magnitude decrease with the series saturable inductor. Further, we observed the most intense x ray output from the low-pressure switch during the initiation or 'trigger delay' period without the series saturable inductor, and after the closure process had begun with the series saturable inductor.

We also measured the variation of the x ray output from the gap at various gas pressures. From this measurement, we observed the x ray output decrease by about 30% when the gas pressure was increased from 1 to 9 mT.

Modeling

We developed a one-dimensional model for the closure regime of the low-pressure switch. In this model, the motions of ions and electrons are modeled by cold fluid equations that include collision ionization and space charge effects. The model equations are parameterized in terms of gas type (ionization coefficient) and pressure; switch gap length and cross-sectional area; and the initial electron density produced by the trigger pulse. This model permits us to follow the space-time evolution of the electric field and the ion and electron current densities in the gap, as well as the total switch current and terminal voltage during switch closure.

We have implemented the model in a general-purpose network and system simulation code. This

Figure 4. Comparison of electrode erosion (a) without and (b) with magnetic delay.

implementation permits the construction of a detailed system simulation model of the test-stand that includes the charging circuit, Blumlein, magnetic switch, and load. We use a magnetic switch model that includes rate-dependent loop-widening of the hysteresis loop, hysteretic losses, minor loops, and hysteresis effects.⁸ Presently, we are validating the low-pressure switch and magnetic switch models against experimental data. Once validated, the complete system model should permit us to study the sensitivity of switch closure performance to magnetic core parameters and to low-pressure switch parameters such as electrode spacing and initial electron density, and thereby provide us with a tool for making switch design tradeoffs.

Future Work

We have demonstrated that the use of a series saturable inductor placed in series with a low-pressure gas spark gap greatly enhances performance. From our measurements, we understand this improved performance to be primarily due to minimizing anode material vaporization during the initial closure of the gap. Without the series saturable inductor, x ray emission occurs

Figure 5. Measured x ray pulse (top curve) and closure (bottom curve) of the low-pressure switch (a) without magnetic delay (0.5 V/div.) and (b) with magnetic delay (0.1 V/div.). Horizontal scale is 100 ns/div.

from the point of triggering until the initial collapse of the gap impedance. The energy deposition into the anode is large as determined by the integrated x ray intensity. With the series saturable inductor, energy deposition into the anode is initiated at the instant the collapse of the gap impedance occurs. The net effect is lower energy deposition into the anode.

From our data, we conclude that with our present triggering method, this switch is capable of operating as either a low-repetition-rate final output switch or, because of the slower closure times at low pressure, as a high-repetition-rate initial commutation switch, i.e., in the initial stages of the power conditioning chain. Although the present triggering device appears adequate, it is difficult to couple a significant portion of the trigger electrical energy into the low-pressure gas. In future work, we will install newly developed, simple, ferroelectric electron emitters as a triggering device.⁹ Current densities from 0.1 to 1 kA/cm² have been extracted from such an emitter for several hundred nanoseconds. Such a device should allow better coupling of the trigger electrical energy to the low-pressure gas. We would therefore expect much faster closure times even at lower pressures.

Our spectral observations indicate that recovery is primarily inhibited by anode vapor remaining ionized in the gap. It is well established that recombination times for metal vapor exceed those of gasses by at least an order of magnitude. Thus, to enhance recovery, we will investigate the use of

anode materials with low heat of vaporization, in order to minimize the accumulation of anode material vapor in the gap.

1. G. Schaefer, M. Kristiansen, and A. Guenther, *Gas Discharge Closing Switches*, Plenum Press (New York, New York), 1990.
2. H.C. Kirbie, G.J. Caporaso, M.A. Newton, and S. Yu, "Evolution of High-Repetition-Rate Induction Accelerators Through Advancements in Switching," *1992 Linear Accelerator Conf. Proc.*, 595 (1992).
3. R.A. Dougal, G.D. Volakakis, and M.D. Abdalla, "Magnetically Delayed Vacuum Switching," *Proc. 6th IEEE Pulsed Power Conf.*, 21 (1987).
4. E.J. Lauer and D.L. Birx, "Low Pressure Spark Gap," *Proc. 3rd Int. Pulsed Power Conf.*, 380 (1981).
5. E.J. Lauer and D.L. Birx, "Tests of a Low Pressure Switch Protected by a Saturable Inductor," *IEEE Conf. Record 1982 15th Power Modulator Symposium*, 47 (1982).
6. T.L. Houck and G.A. Westenskow, "Status of the Choppertron Experiments," *1992 Linear Accelerator Conf. Proc.*, 498 (1992).
7. S. Humphries, *Principles of Charged Particle Acceleration*, John Wiley and Sons, Inc. (New York, New York), 283ff (1986).
8. A.N. Payne, "Modeling Magnetic Pulse Compressors," *Conf. Record 1991 Particle Accelerator Conf.*, 3091 (1991).
9. H. Riege, *New Ways of Electron Emission for Power Switching and Electron Beam Generation*, European Organization for Nuclear Research, Report CERN-PS 89/42(AR) (1989).

**DATE
FILMED**

1 / 7 / 94

END