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INVITED

REPORT OF WORKSHOP ON REPETITIVE OPENING SWITCHES*

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Abstract

A workshop on Repetitive Opening Switches was conducted by Texas Tech University for the U.S. Army Research Office. Several papers on a wide range of innovative opening switch concepts were presented. Discussions about the research needs to advance the state-of-the-art in this important, emerging field are summarized. A concensus on research topics and their importance is summarized and a suggested research priority list given.

Introduction

A Workshop on "Repetitive Opening Switches" was sponsored by the U.S. Army Research Office and conducted by Texas Tech University at Tamarron, Colorado on January 28-30, 1981. The workshop was attended by 40 participants from universities, industry, national laboratories, and government agencies. Except for an initial, classified briefing (conducted at the Air Force Weapons Laboratory in Albuquerque) the workshop presentations and deliberations were unclassified. The underlying reasons for the interest in repetitive opening switches were summarized by DoD and DoE representatives. Several of the workshop participants then made formal presentations and most of their papers are included in the Workshop Proceedings.

The goals of the workshop were to examine the state-of-the-art in repetitive opening switches and to establish the most important and fruitful research areas and set priorities for advancing the capability in this important field. Some suggested parameters for discussions at this workshop were:

Switch hold-off voltage	$V_{oc} > 10$ kV
Switch current	$I > 1$ kA
Switch opening time	$\tau_{open} < 1\mu s$
Pulse Repetition rate (pulses per second)	PRR > 10 pps

Since there have been very few successes to date in repetitive opening switches, it was deemed necessary to include discussions on single shot switches (e.g. fuses) and counterpulsed systems (e.g. vacuum interrupters) to set the backgound for the discussion about the more difficult goal set for this workshop.

The interest in repetitive opening switches is caused by the potentially high energy storage density that can be achieved through the use of inductive systems (at least one order of magnitude higher than that of capacitive systems). The key technological problem in developing a successful inductive energy storage system is the opening switch. When attempting to open a conducting switch rapidly in an inductive system the $L\frac{di}{dt}$ effect results in a very high voltage across the switch which tends to maintain a conducting arc between the switch electrodes. How to interrupt the conduction process against a high driving voltage is the essence of the opening switch problem. For repetitive switching it is particularly important that the interruption process is highly efficient so that the losses do not change the basic behavior of the interruption process. For purely inductive loads there are fundamental constraints to this efficiency but in the case of resistive loads the efficiency can, in principle, be very high and it is important to seek switches with the most efficient control of the discharge interruption mechanism.

Table I shows some sample problem areas of current interest where repetitive opening switches would be very valuable and Table II shows some examples of useful pulse length applications. In this research field a wide range of sub-disciplines are needed, as indicated by the simplified chart in Fig. 1.

Workshop Summary

From the presented papers and the discussions that followed, it is clear that the state-of-the-art for single shot and counterpulsed switches is quite impressive. It is, however, difficult to envision an extension of these concepts to high repetition rate, low jitter, long life operation. These concepts may still be of interest for single burst-mode operation and as test switches for other components in the development of viable inductive energy storage systems. They are also useful in what one can learn about how opening

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14. ABSTRACT

A workshop on Repetitive Opening Switches was conducted by Texas Tech University for the U.S. Army Research Office. Several papers on a wide range of innovative opening switch concepts were presented. Discussions about the research needs to advance the state-of-the-art in this important, emerging field are summarized. A concensus on research topics and their importance is summarized and a suggested research priority list given.

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switches work, and in providing test cases for analytical models. It was argued that the counterpulsed SCR's or vacuum interrupters could achieve respectable repetition rates and lifetimes. This seems especially to be the case for the SCR's but it appears that the combination of the cost of the solid state material and the required counterpulsing circuit will make such a system costly and that it may also be energy inefficient and bulky (large size and weight). Other semiconductor devices, such as the Hall effect switch described in one of the workshop presentations, do not have the counterpulsing requirement and may hence prove to be lighter, more efficient, and less expensive than SCR's.

Much of the interest of the workshop participants was directed towards electron beam and optically controlled discharges. Several laboratories are conducting or planning experiments along these lines. It was clear, however, that much needed basic information is not available and that this makes it impossible to make an adequate analytical assessment of these concepts at the present time. It was felt that code-developments, coupled with experiments, were particularly needed. This work must also pay close attention to the poorly understood plasma chemistry in these switches and develop models for discharges and discharge processes.

For all switches it is important to pay attention to the energy efficiency of the switch in terms of energy switched and the energy consumed. Some switches, such as the e-beam sustained switch and the counterpulsed switches, have unique problems related to their particular interruption techniques (i.e. the e-beam and the counterpulse systems, respectively). Particularly important is the question if a particular switch concept can be developed to sustain the inductor charging current for a time considerably longer than the output pulse length. In other words, what kind of pulse compression can be expected? A reasonable criterion seems to be that the ratio of inductor charging time to output pulse length should be larger than 10. In principle, this can be overcome by using a staged switch system where a slow, high current switch is used to build up the inductor current. This switch is then opened, transferring the current to a parallel, fast switch with less Coulomb ($\int idt$) capability which opens when the first switch has recovered, thereby effecting a pulse sharpening. This concept has been applied in USSR single shot inductive energy storage systems where as many as 3 successive pulse sharpening switches have been used and in the NRL Trident system. Such a scheme increases the cost, size, and complexity and tends to reduce the reliability of the switch system and is better avoided, if possible. The basic concept of staged opening switches can also be used to provide a limited burst of output pulses from an inductive energy storage system. This scheme may well be a first step in developing fast, repetitive opening switches.

Obviously, several of the participants felt particularly strongly about the switches which they were closely associated with. An effort has ben made to summarize and compare some near and far term capabilities of some of the switches in Table III. The numbers in ( ) indicate the long term expected performance parameters. This table should obviously be read with caution since the numbers represent in some cases a very limited opinion sample (ranging from 1-10). These numbers have not been reviewed or verified in any other manner. It was felt, however, that the numbers represent the best "educated guesses" of active researchers in the field and hence are useful.

Efforts were made to outline the basic research issues which would lead to a better understanding and hence better design procedures for repetitive opening switches. These discussions were organized by workshop subgroups under the direction of E. Kunhardt, M. Parsons, P. Turchi, and I. Vitkovitsky. Switches with limited burst mode operation potential were also included for completeness.

The results of these discussions and recommendations are summarized in Table IV. Note that these research issues are not prioritized since this was not a direct goal of the workshop. An effort has been made, however, by the authors of this paper to prioritize some of the research issues, as shown in Table V.

It is clear that a cooperative research program between pulsed power technologists, plasma physicists, atomic and molecular physicists, plasma chemists, material scientists, and surface physcists is called for. Such a planned, coordinated program between research groups with the right expertise is expected to offer the best chance for rapid improvements in the understanding of the complex, interrelated problems at hand. No single research group seems to possess all the required expertise but combinations of a few groups should be able to cover all the most important basic phenomena without excessive administrative coordination problems.

Much of the needed research is also of importance to the development of advanced gas discharge lasers (e.g. diffuse discharges at high voltage and high repetition rates). Much of their past and present code development work may prove to be very valuable to the opening switch problem. In the areas of materials problems and gas flow dynamics there are also clear common interests with researchers in the area of repetitive closing switches.

A switch concept which was not discussed in any depth at the workshop was that of magnetic switching using saturable materials, such as ferrites or metglass This was primarily due to the lack of attending experts in this field. Brief discussions indicated, however, that this topic deserves more consideration than it received.

Some important points to remember about opening switches are:

- Energy required to open the switch can be divided in two parts:
    1) Fundamental (flux conservation, internal losses)
    2) Technical (energy required to move switch contacts or change conductivity).
- Importance of stray inductances and magnetic energy stored in the switch itself compared to the switching energy
- Importance (especially from an engineering viewpoint) of taking the energy to operate the switch from the inductive store itself and not from another source, such as a separate capacitor bank.

The need for novel ideas in this field is clear. It is, by no means, certain that any of the proposed schemes to date can be extrapolated and engineered in the high power, high repetition rate, long life regimes of primary interest. The research area is one of high risk and of potentially extremely high pay-off.

It is believed that the workshop served as a very useful function and stimulated new ideas and thoughts in this important field. Another workshop is recommended on the same basic topic about 2 years from this first one. A workshop on discharge modeling and accompanying verification experiments is also recommended as soon as possible.

Table I

SOME TYPICAL SWITCH REQUIREMENTS OF CURRENT INTEREST

	Directed Energy Weapons	Inertial Confinement Fusion	Electric Launchers (Guns)
V_{oc}	.1-1 MV	3 MV	5-20 kV
Pulse Repetition Rate	$5\times(10^3-10^4)$	10 pps	100-500 pps
I_{peak}	10-100 kA	100 kA	1-5 MA
Life	10^6-10^8 shots	10^9 shots	10^6-10^8 shots
Turn-on Time	$\sim$ μs	< μs	< ms

Table II

SOME EXAMPLES OF USEFUL PULSE LENGTHS

FOR VARIOUS APPLICATIONS

1) $\tau_p \lesssim 100$ ns: (replaces water line)

e.g. $\sim 10^4$ pps, ~ 1 MV (Beam Weapon)

$\sim 10^2$ pps, ~ 1 MV (Inertial Confinement Fusion Reactor)

<.01 pps, ~ 1 MV (Simulation)

2) $\tau_p \sim 1-10$ μs: (Capacitor or water line charging or direct transfer to resistive load)

e.g. Beam Weapons, ICF Reactor, Simulator with V and pulse repetition rate as above, or Laser Weapon with 10-100 pps and .1-1 MV.

3) $\tau_p \sim 1$ ms: (to resistive load)

e.g. drive of iron-core betatron (beam weapon) with 100 kV/turn, 10-100 kA, ~ 10 pps or electromagnetic propulsion

Table III

SUGGESTED OPERATING PARAMETERS FOR SOME REPETITIVE OPENING SWITCH CANDIDATES

Parameter / Switch Concept	V_{oc} (V)	V_{closed} (V)	J (A/cm^2) or I (A)	$\frac{dI}{dt}$ (A/s)	Max. cw Reprate (pps)	Max. Burst Reprate	Life (Shots)	Needed Research
Electron Beam Controlled	$2\times10^4-5\times10^5$ (10^6)	$10^3-2\times10^4$ $(<10^3)$	$10-10^3$ A/cm^2 10^3-10^5 A $(10^6$ A)	$10^{11}-10^{13}$ (10^{14})	$1-10^3$ (10^3-10^5)	$25-10^5$ (10^5-10^6)	10^3-10^5 (10^6-10^8)	Plasma chemistry, gas dynamics, electrode materials
Optically Controlled	10^5	10^3	10^4 A	10^{12}	10^4			Molecular Physics
Dense Plasma Focus	$5\times10^4-3\times10^5$	10^2-10^3	10^5 A/cm^2 $4\times10^4-10^6$ A	5×10^{12}	25	10^5		Effects of B.C. on focus formation, Repeatability
Plasma Erosion	10^6		10^6 A	10^{14}		$>10^3$		
Reflex Discharge	$<10^6$ (10^5-10^7)	$3-4\times10^4$ $(1-15\times10^3)$	5×10^4 A/cm^2 $(>10^5$ $A/cm^2)$	$(>10^{13})$	$.5-1\times10^3$	$2-10\times10^3$		Proof of concept
Spoiled Electrostatic Conf.	10^4 (10^5)	500 (300)	3 A $(10^3$ A)	10^5 (10^8)	10^3 (10^5)	10^3 (10^5)	10^5	Scaling
Controlled Plasma Instabilities	$1-3\times10^5$	10^3	10^6 A/cm^2 10^5 A	10^{13}	10^4	10^5		Plasma Physics
$\bar{J} \times \bar{B}$ (Thyratron)	5×10^4	10^3	200 A	2×10^8	$>10^3$			Plasma-Wall-B field interfaces
SCR (Counterpulsed)	5×10^3 (10×10^3)		4.5×10^3 A $(10^4$ A)	5×10^8 (2×10^9)	$2-4\times10^4$ (5×10^4)	$2-4\times10^4$ (5×10^4)	10^7-10^8 $(10^{10}-10^{15})$	Pulse rating of SCR's

Table III (continued)

Parameter Switch Concept	V_{oc} (V)	V_{closed} (V)	J (A/cm^2) or I (A)	$\frac{dI}{dt}$ (A/s)	Max. cw Reprate (pps)	Max. Burst Reprate	Life (Shots)	Needed Research
Vacuum Interrupter (Counterpulsed)	$3.5x10^{4}$ $-2x10^{5}$	50	$25x10^{3}$ A (10^{5} A)	$10^{9}-10^{10}$	25 (50)	25 (50)	$10^{3}-10^{5}$ ($10^{5}-10^{6}$)	Electrode Material, Recovery
Fuse	10^{6}		$25x10^{7}$ A/cm^2 (10^{8} A/cm^2)	$3x10^{13}$ ($>10^{14}$)		(6 pulses, Multistage)		Discharge media
Explosive (Chemical)	$.4-1x10^{6}$		$3x10^{5}$ A	$2x10^{13}$				
Crossed Field Tube	10^{5} ($2.5x10^{5}$)	500 (200)	10^{4} A ($2x10^{4}$ A)	10^{9} (10^{10})	10^{2} (10^{5})	10^{5}	$3x10^{7}$ (10^{9})	
Vacuum Arc Interrupter	$2.5x10^{4}$ (10^{5})	20-30	10^{4} A ($5x10^{4}$ A)	$5x10^{9}$ ($>10^{10}$)	10^{3} ($1-5x10^{4}$)		10^{8} Coulomb transfer	Increased current capability-paralleling
Hall Effect	0.8 kV (1.6 kV/cm)	8 V (16 V/cm)	3.4 kA/cm^2	$4x10^{10}$ A/cm^2-s	10^{5} pps (10^{6} pps)			Research on Hall effect material
Magneto-Plasma Dynamic	10^{5} V/cm	$1-3x10^{3}$ V/cm	$3x10^{5}$ A/cm^2	10^{12} A/cm^2-s	10^{5} pps			Power flow at vacuum-plasma edge

TABLE IV

BASIC RESEARCH ISSUES

BASIC RESEARCH PROBLEMS	RESEARCH APPROACH	SWITCH CONCEPT
1. Discharge modeling and comparative experiments. Code development to produce circuit model. Inclusion of plasma chemistry.	Develop codes and carry out carefully planned experiments to check the code validity. Develop user oriented codes that enables the nonexpert to state problem in electrical circuit terms. Include plasma chemistry effects in the code.	Depending on the code (several will be needed) this applies to essentially all the gas discharge switch concepts. Particularly obvious ones are the electron beam and optically controlled, diffuse discharge switches
2. Compile and measure (when needed) fundamental data such as rate coefficients, cross-sections, etc.	Conduct literature search. Carry out basic measurements for gases and gas mixtures under conditions of interest to 1. & 3.	Essentially all gaseous switches, but especially those in 3..
3. Production of diffuse discharges. Establish conditions for arc development. Develop fundamental understanding to enable choice of gas mixtures with high breakdown field, high conductivity in conducting phase, fast recovery, etc.	Carry out a series of comparable experiments, utilizing input from 2. above, to determine optimum gas mixtures, pressures, and excitation conditions for diffuse discharge switches	Electron beam and optically controlled. Crossed field tube, spoiled electrostatic confinement, reflex discharge, plasma erosion, thyratrons
4. Electrode phenomena. Surface physics of arc and diffuse discharges (e.g. sputtering) Photo-electric effect.	Conduct a careful experiment involving several gases, mixtures pressure, discharge conditions, etc., to establish the "best" electrode materials.	Essentially all gas discharge switches (including vacuum interrupter).
5. Motion of conducting plasma due to applied B-field. Effect of nonuniformities (asymmetries) in conduction channel on B field interaction.	Study interaction of high current plasma discharges with the vacuum/plasma/field interfaces manipulated electromagnetically to explain such features as residual plasmas (outside main conduction region), propagation of electromagnetic energy in plasma/vacuum field environment, energy dissipation, low density-high current conduction, etc.	$\frac{dL}{dt}$, Dense plasma focus, Magneto-plasma-dynamic
6. Plasma instabilities. Non-classical transport phenomena (Generated beams, anomalous resistivity, etc.)	Identify conditions for "triggering" plasma instabilities. Utilize information developed in fusion research and adapt to partially ionized, low temperature discharges. Conduct comparative experiments.	Dense plasma focus. Magneto-plasma-dynamic. Macro- and micro-instabilities.
7. Effects of quenching media on inductive and resistive fields and the hydrodynamics of the media and their heating/cooling rates. Investigations of conductivity, diffusion mechanisms, breakdown energy requirements, etc.	Make systematic studies, under comparative conditions, of a wide range of quenching materials (solid, gas, liquid). Instrument for careful, V, I, T measurements. Interpret chemistry involved.	Fuses JxB and magneto-plasma-dynamic devices with quenching medium.
3. Develop superconducting materials with improved stability and higher transition temperatures.	Fundamental materials development.	Superconducting switches

TABLE IV (Continued)

BASIC RESEARCH PROBLEMS	RESEARCH APPROACH	SWITCH CONCEPT
9. Flow dynamics in gas and liquid interrupters. Arc cooling rates. Recovery rate, effect of contamination	Carry out measurements under controlled conditions with varying flow velocities, current densities, and electric fields	Gas and liquid interrupters
10. Magnetic switch material development	Develop materials with high μ_r, B_{sat}, low loss	Magnetic (saturable inductor)switches.

TABLE V

SUGGESTED RESEARCH PRIORITIES

1a) Discharge Modeling (including plasma chemistry) and Comparative Experiments.

1b) Production of Diffuse Discharges with High Hold-off Voltage, High Conductivity, High Current Density, and Fast Recovery.

1c) Measurements of Basic Data Needed in a) and b) Above, such as Cross-sections, Rate Coefficients, etc.

2a) Motion of Gas Discharges in Magnetic Fields.

2b) Plasma Instabilities, Non-classical Transport Phenomena.

3) Determine the Limits to Various Solid State Switching Schemes

4) Electrode Surface Physics of Arc and Diffuse Discharges

5) Effects of Quenching Media on Discharges

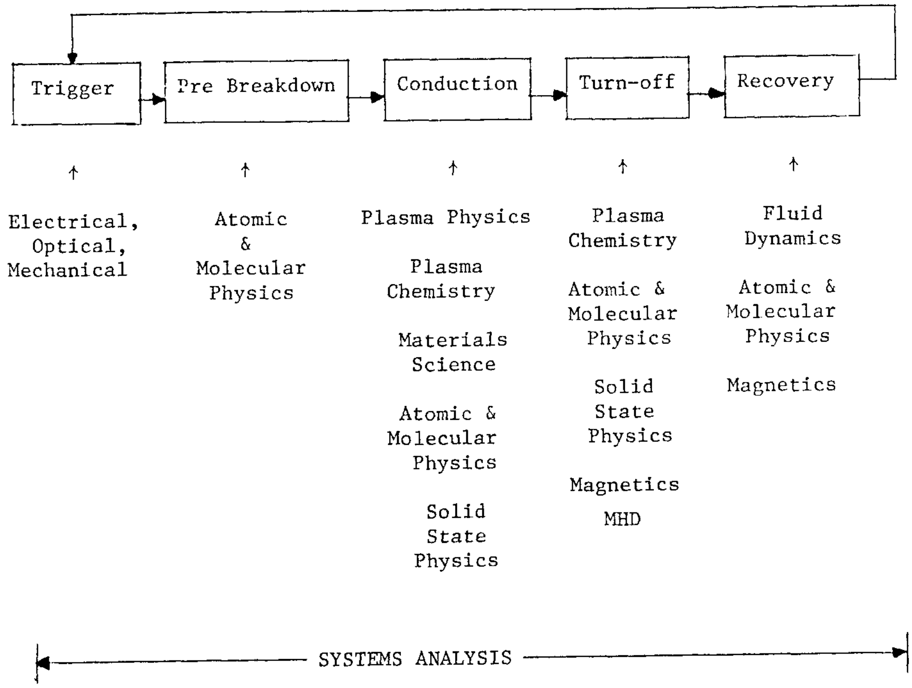

Fig. 1 Schematic Representation of Opening Switch Operations Sequence and Some Related Research Topics.