

# EVALUATION OF INNOVATIVE HIGH PULSE RATE, PURGED SPARK GAP CONCEPTS

W.J. Thayer, C.H. Lo, and A.K. Cousins

Spectra Technology Inc.  
2755 Northup Way  
Bellevue, Washington 98004

## Introduction

High pressure spark gaps have been used in a pulse charged mode for many single pulse and low pulse repetition rate modulators and other pulsed power devices. High power, high pulse repetition rate modulators require that spark gaps or other switches recover over a period that is less than the interpulse time. The recovery rate can be greatly enhanced by actively purging the spark gap.[1,2] This paper addresses some of the issues that must be dealt with in developing purged spark gaps for high average power, extremely high peak power pulsed devices.

The size of the spark gap, the size and complexity of ancillary equipment, and the power required to purge the gap greatly affect the practicality, efficiency, and cost of blown spark gaps. The ancillary equipment for purging a spark gap must supply the volume of gas needed for recovery and deal with large amplitude pressure waves generated by the spark.[2,3] In addition it must deal with the pulse energy and average power, especially with the energy radiated to the spark gap electrodes and dielectric walls. For closed loop gas flow systems, the average power dissipated in the spark gap must be removed so that cool gas can be returned to the spark gap. At high pulse rates, the flow circulation power can exceed the switched electrical power and greatly reduce the net switch efficiency.[3] New approaches are needed to provide efficient high-pulse-rate, high power spark gaps.

The analysis, design, and experimental work that is discussed below have characterized some of the issues of high pulse rate spark gaps and explored the practicality and feasibility of several innovative approaches. These approaches include configuring the spark gap purge flow channel so that the shock waves and unsteady flow generated by the spark hasten recovery. This concept, Figure 1, referred to as "tuning" of the flow channel, has been successfully demonstrated[2,3,4], and reduces purge flow requirements by a factor of approximately two and circulation power by a factor of ten or more. A second approach is to use a condensable dielectric gas in the spark gap, condensing it in the gas recirculation system and vaporizing it again at the spark gap. Gases such as steam, ammonia, chlorofluorocarbons, and others could be used. A closed purged system which uses a condensable fluid will reduce the power for recirculating the purge gas by approximately three orders of magnitude. The condensable dielectric medium provides a mechanism for cooling the spark gap through the use of a two-phase, gas-droplet mixture.

## Purged Spark Gap Systems

The spark gap switch overall efficiency can be adversely affected by gas circulation power requirements. A spark gap with conventional "wind tunnel" type flow system[1] is shown schematically in Figure 2a. In this system, flow power,  $P_c$ , is added to the gas stream by a compressor to raise the pressure sufficiently that it will flow through the spark gap and around the flow loop at the desired rate. Power that is dissipated in the dielectric

gas in the spark gap,  $Q_s$ , is removed by a heat exchanger as is heat added due to compressor inefficiencies and adiabatic heating,  $Q_c$ .

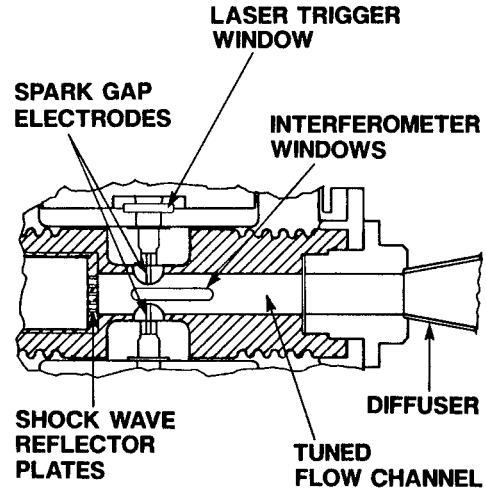


Figure 1. Test Spark Gap Using "Tuned" Unsteady Flow.

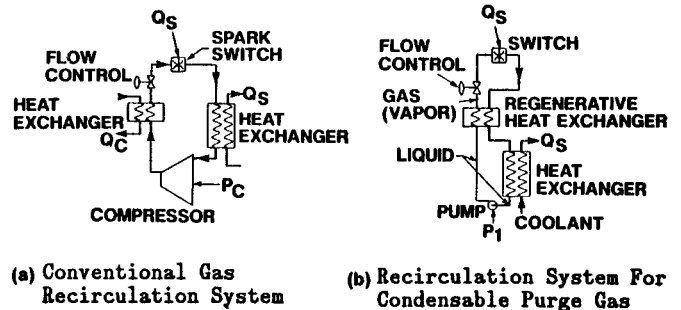


Figure 2. Alternative Systems for Circulating Spark Gap Purge Flow

For a closed gas purge system, the power lost in circulating the purge gas,  $P_{loss}$ , is the product of the volume flow rate of gas through the switch and the pressure loss through the gas circulation system. The pressure loss is the sum of the losses in the spark gap, flow ducting, and heat exchangers and other equipment that are necessary to return the purge gas to a cool, electrically insulating condition.  $P_{loss}$  can be related to a number of spark gap and flow parameters, i.e.,

$$P_{loss} = K \frac{\rho_s A}{2} \Delta x^3 f^3 \quad (1)$$

Here the velocity of the purge gas past the electrodes is equal to the product of the distance that the spark residue must be purged between pulses,  $\Delta x$ , and the pulse rate,  $f$ . The flow cross sectional area at the spark gap is  $A$ , the gas density is  $\rho$ , and  $K$  is a system dependent loss

| Report Documentation Page                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                    |                                     |                                             | Form Approved<br>OMB No. 0704-0188          |                                    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|-------------------------------------|---------------------------------------------|---------------------------------------------|------------------------------------|
| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. |                                    |                                     |                                             |                                             |                                    |
| 1. REPORT DATE<br><b>JUN 1989</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                    | 2. REPORT TYPE<br><b>N/A</b>        |                                             | 3. DATES COVERED<br><b>-</b>                |                                    |
| 4. TITLE AND SUBTITLE<br><b>Evaluation Of Innovative High Pulse Rate, Purged Spark Gap Concepts</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                    |                                     |                                             | 5a. CONTRACT NUMBER                         |                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                             | 5b. GRANT NUMBER                            |                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                             | 5c. PROGRAM ELEMENT NUMBER                  |                                    |
| 6. AUTHOR(S)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                    |                                     |                                             | 5d. PROJECT NUMBER                          |                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                             | 5e. TASK NUMBER                             |                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                             | 5f. WORK UNIT NUMBER                        |                                    |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><b>Spectra Technology Inc. 2755 Northup Way Bellevue, Washington 98004</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                    |                                     |                                             | 8. PERFORMING ORGANIZATION<br>REPORT NUMBER |                                    |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                    |                                     |                                             | 10. SPONSOR/MONITOR'S ACRONYM(S)            |                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                             | 11. SPONSOR/MONITOR'S REPORT<br>NUMBER(S)   |                                    |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br><b>Approved for public release, distribution unlimited</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                    |                                     |                                             |                                             |                                    |
| 13. SUPPLEMENTARY NOTES<br><b>See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                    |                                     |                                             |                                             |                                    |
| 14. ABSTRACT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                    |                                     |                                             |                                             |                                    |
| 15. SUBJECT TERMS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                    |                                     |                                             |                                             |                                    |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     | 17. LIMITATION OF<br>ABSTRACT<br><b>SAR</b> | 18. NUMBER<br>OF PAGES<br><b>4</b>          | 19a. NAME OF<br>RESPONSIBLE PERSON |
| a. REPORT<br><b>unclassified</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | b. ABSTRACT<br><b>unclassified</b> | c. THIS PAGE<br><b>unclassified</b> |                                             |                                             |                                    |

parameter. The strong dependence on pulse rate is seen. It is immediately apparent from Eqn. 1 that the purge distance must be minimized. In addition, the spark gap area should be made as small as is consistent with holding the voltage across the gap and preventing surface flashover.

Figure 3 shows the flow power that is consumed by pressure losses in the gas as a function of pulse rate relative to the switched electrical power. A comparison is made between the initial "tuned" spark gap and a conventional wind tunnel type configuration. Here, a tuned spark gap of the approximate size of the test switch discussed below. Approximately 15 J/pulse was dissipated by the spark in the gas, while the switched energy was approximately 110 J. The conventional spark requires approximately twice the purge flow velocity for purging according to detailed analyses of recovery, [3] and is assumed to have twice the cross sectional area as the tuned spark gap. At low pulse rates, the flow circulation power is negligible in both cases. At pulse rates of several kilohertz or higher, the flow losses become a significant fraction of the switched electrical power. The conventional spark gap has approximately sixteen times the circulation flow losses as the initial tuned spark gap.

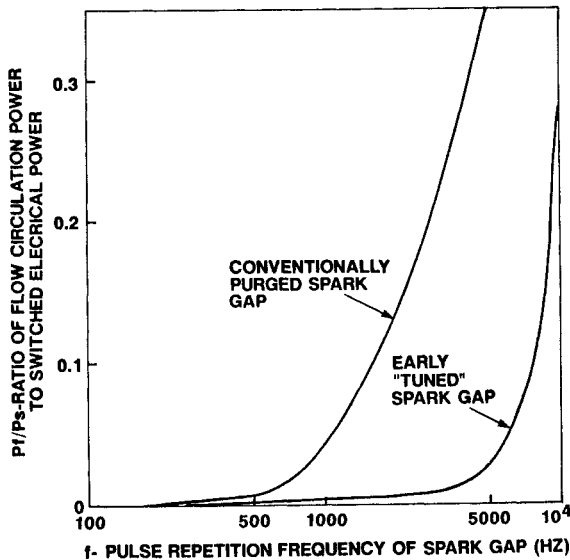


Figure 3. Dependence of Spark Gap Purge Flow Losses on Pulse Rate.

The power,  $P_c$ , required for circulating the purge gas can be related to the pressure ratio, PR, across the compressor in Figure 2a, and to flow parameters, i.e.

$$P_c = \frac{\dot{m}}{\eta_c} \frac{\gamma}{(\gamma-1)} \frac{P_s}{\rho_s} [PR^{(\gamma-1)/2} - 1] \quad (2)$$

where  $\dot{m}$  is the mass flow rate through the spark gap,  $P_s$  is the gas pressure in the spark gap,  $\rho_s$  is the gas density,  $\gamma$  is the specific heat ratio of the gas, and  $\eta_c$  is the efficiency of the compressor. The efficiency of compressors appropriate for the purging conditions is 50-70 percent, implying that the impact on system efficiency is twice that of the flow losses.

Another of the purging concepts is to use a dielectric gas that can be condensed in the flow circulation system, pumped to the required spark gap inlet pressure, partially or completely vaporized while removing heat from the spark gap, and used again to purge the gap. The appropriate

recirculation system is shown in Figure 2b. The regenerative heat exchanger transfers heat from the hot spark residue into the returning fluid to vaporize it again. A major advantage of this system from an efficiency viewpoint is that the

recirculation flow power is much less for pumping a liquid than pumping a gas. The pump power required to recirculate fluid is;

$$P_p = \frac{\dot{m}}{\eta_p} \frac{P_s}{\rho_l} [PR - 1] \quad (3)$$

where  $\rho_l$  is the liquid density, PR is the pressure ratio, and  $\eta_p$  is the pump efficiency. Pressure losses are expected to be similar for the condensable fluid and conventional gas systems, as are the other parameters in Equations 2 and 3, except the densities. The fact that the liquid density is approximately 1000 times the gas density reduces the input pump power requirement by approximately three orders of magnitude. The recirculation power is therefore very small for the condensable fluid system relative to the conventional gas system. This will be very important for high pulse rate operation.

#### High Pulse Rate Spark Gap Cooling

Analysis has been done to evaluate the rate of heat transfer to the spark gap interior walls. [2,3] Radiation from the spark residue dominates the wall heating. This analysis showed that approximately half of the energy that is deposited in the gas is radiated from the spark residue prior to a subsequent pulse. Measurements of losses in test spark gaps [3,5] and predictions of these losses for high power switches indicate that ten percent or more of the energy transferred through the spark is lost in the arc. Essentially all of the energy that is radiated from the spark is absorbed by the walls. Figure 4 shows the computed wall temperature as a function of time after the first spark for a spark gap of similar geometry to the test device operating at a 10 kHz pulse repetition frequency. Very intense heating occurs shortly after the spark, when the spark residue expands to a large size and is still very hot. The wall surface temperature rises very quickly due to rapid energy absorption during times when conduction heat transfer into the wall is ineffective. At longer times during each pulse, conduction into the bulk dielectric material cools the surface. Over ten pulses, the wall temperature will rise dramatically, as seen in Figure 4. Such rapid heating will cause thermal shock, differential thermal expansion that will severely stress the wall material, and ultimately melt the wall.

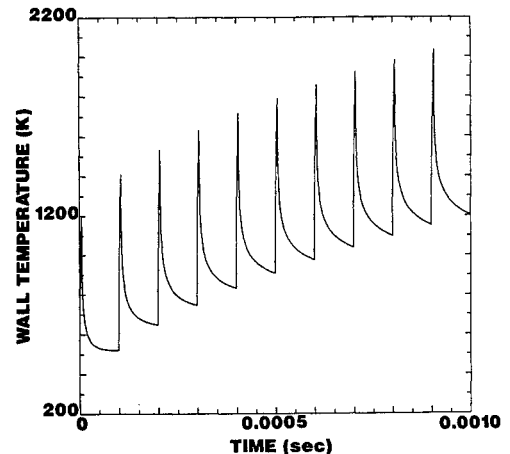


Figure 4. Computed Spark Gap Wall Surface Temperature for Repetitively Pulsed Operation.

Injection of a two-phase dielectric medium, i.e. a mixture of dielectric gas and small droplets or a liquid film, can provide a very high heat transfer capacity and high heat flux from the wall.[3] The heat transfer rates that can be achieved using spray cooling are much higher than can be achieved using convective gas cooling, even at very high flow rates.[6] One spark gap geometry that would provide a cooling layer near the spark gap walls and a region of dielectric gas that was free of liquid near the electrodes is shown in Figure 5. The fact that a liquid film can be located near the wall and that the heat of vaporization of the liquid provides a very high thermal capacity means that the walls can be cooled with a low flow rate of coolant. The liquid medium on or near the spark gap wall will quickly remove heat from the internal surface and minimize thermal stress problems. The large volume change due to evaporation will generate sufficient flow rates of gas to effectively purge a spark gap at high pulse rates.

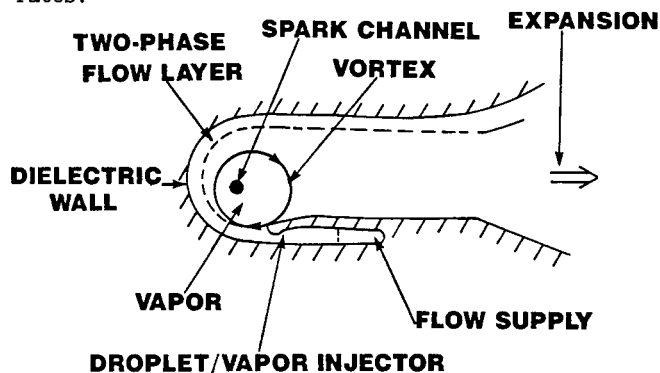


Figure 5. Two-Phase Flow Purged/Cooled Spark Gap.

The evaporation of the liquid phase to produce gas phase dielectric gas for purging the spark gap effectively fills the role of the regenerative heat exchanger in Figure 2b. Heat that is rejected by the spark is used to heat and vaporize the incoming liquid phase of the dielectric gas stream. Thus it is not necessary to have an external component to provide this heat transfer function, and a simpler spark gap ancillary system is possible using the two-phase spark gap cooling and vapor generation technique.

#### Tuned Spark Gap Modeling and Test Results

A one-dimensional, unsteady flow code was developed to solve the mass, momentum, and energy conservation equations which govern the purging process in a spark gap flow channel following arc formation.[2,3] In this model, gas properties and spark gap flow channel area varied with distance along the flow axis from the spark gap and with time. Geometric features such as wave reflector plates, electrodes, constant cross-sectional area regions, and expansions or diffusers were included. Pressure, temperature, number density, velocity, and internal energy were computed for all locations in the spark gap flow channel as a function of time under repetitively pulsed conditions. This model was used to compute both the breakdown voltage for a path directly between the electrode tips, which is proportional to  $N_1 D$  where  $N_1$  is the number density between the electrodes and  $D$  is the distance between electrodes, and for the path near the dielectric walls and through the spark residue, which is proportional to  $N_2 D_2$ , where  $N_2$  is the effective spark residue number density and  $D_2$  is the path length through the hot residue.

Radiation heat transfer from the spark and spark residue was analyzed in steps from spark formation through the relaxation of the spark medium.[2,3] These steps were the very short spark growth period, an expansion and "cooling wave" period, and finally a long period when the spark residue was purged from the gap. The analysis showed that approximately 7.8 J of the typical 16 J dissipated in the spark, or approximately 50 percent of this energy, was radiated away prior to a subsequent spark.[3] This was typical of the range of spark energies and sizes considered during the analysis and test discussed below.

A repetitively pulsed spark gap which incorporated the tuned, unsteady flow geometry was developed and tested.[2,3,4] The electrode separation was 2.4 cm for the tests reported here, the flow channel height 3.3 cm between electrode walls, and the width was 5.6 cm. One wave reflector plate was located 4.0 cm upstream of the spark gap, a 20.0 cm long constant area flow channel was used downstream of the electrodes to tune the pressure wave arrival times. This was followed by a diffuser which increased the flow channel area by 5.0 in a length of 23 cm. The spark gap was mounted on the end of a 1.5  $\Omega$  water pulse forming line. An impedance matching load resistor was located between the pulse forming line and the spark gap. The charging pulses were supplied by a five pulse modulator. The transfer pulse current waveform was monitored using a coaxial current viewing resistor. The voltage across the spark gap was measured using a capacitive voltage divider. The charge time for the spark gap was approximately 10  $\mu$ s to reach the peak voltage of approximately 65 kV (the DC breakdown voltage). The total charge transfer was approximately 1.5 millicoulomb. The spark was triggered using a uv wavelength laser which was focused on the gas between the electrodes.

The recovery experiments used the second high voltage pulse to measure the hold-off voltage as a function of time after the first spark. The energy dissipated in the spark was constant, approximately 15 J of the total energy transfer of approximately 110 J during these tests. The timing of the spark trigger could be varied relative to the pulse forming line charge pulse, and was monitored using a photodiode. The breakdown voltage, either due to triggering or self-breaking, was measured for a range of pulse repetition rates and flow rates. The breakdown voltage is plotted as a function of the interpulse time in Figure 6 for a purge flow rate of 150 m/s, as are predictions for these operating conditions. It was observed that at low interpulse times prefireing always occurred and that the holdoff voltage was quite nonrepeatable, as seen for times less than  $\sim 0.4$  ms. At longer times the holdoff voltage increased toward the dc holdoff voltage, approximately 65 kV, and became quite repeatable as seen for times longer than 0.4 ms. This transition corresponded to a transition from breakdown through the hot residue downstream of the electrodes to breakdown between the electrode tips.[3] When the hot residue had been purged less than 3.2 cm from the electrodes, the switch prefired through the hot residue and the full recovery voltage could not be achieved. Due to the reverberation of pressure waves in the spark gap, the recovery voltage dropped at some discrete interpulse times, as seen around 0.6 and 0.9 ms in Figure 6. The variation in recovery voltage corresponded to variations in the number density between the electrodes. The data show that the spark gap fully recovered at 2.5 kHz operation at this purge rate.  $N_1 D_1$  is also affected by the passage of thermal disturbances caused by the interaction of pressure waves with the mean flow

pressure recovery downstream of the wave reflector plate. These "entropy waves" [4] are convected toward the spark gap and can significantly affect the density. A high density period predicted around 0.4 ms in Figure 6 was caused by an earlier high pressure period. As seen in Figure 6, the 1-D flow model provides a good representation of the dominant recovery processes.

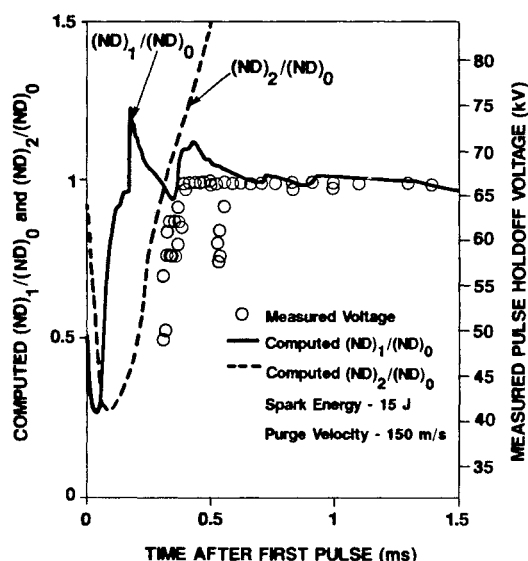


Figure 6. Comparison of Computed ND Products with Measured Holdoff Voltage.

### Conclusions

Several innovative concepts for efficiently achieving full spark gap recovery at high pulse rates were evaluated. These included "tuning" the purge flow channel to control the spark residue relaxation and unsteady flow, the use of condensable dielectric gases, using two-phase purge media for spark gap cooling and purge gas generation, and combinations of these techniques. Analysis showed that the purge flow power required for high pulse repetition rate spark gaps can be reduced by several orders of magnitude relative to conventional approaches by using these techniques. Modeling also showed that the severe thermal problems of high power spark gaps can be alleviated by the two-phase flow approach. Tests of the tuned flow spark gap demonstrated full recovery at pulse rates to 2500 Hz and substantial reductions in purge gas requirements. Predictions of the computational model compared very well with test data.

### Acknowledgement

This work was sponsored in part by the Department of Energy, contract DE-AC03- 85SF15930, and by Spectra Technology Inc.

### References

- [1] Kuhlman, J.M. and Molen, G.M., "Performance of High-Power Gas Flow Spark Gaps," AIAA Journal, Vol. 24, No. 7, July 1986, p 1112.
- [2] Thayer, W.J., Lo, C.H. and Cousins, A.K., "Unsteady Flow Aspects of Purged Spark Gap Recovery," AIAA Paper 89-0223, 27th Aerospace Sciences Meeting, Reno Nevada, January 1989.

- [3] Thayer, W.J., Lo, C.H. and Cousins, A.K., "Pulse Rate Spark Gap Evaluation," Final Report 1356.1 to DOE, Spectra Technology, Inc., October 1988.
- [4] Thayer, W.J., Lo, C.H. and Cousins, A.K., "Recovery of a High Pulse Rate Spark Gap Switch," Conference Record for the 18th Power Modulator Symposium IEEE Publication 88CH2662-5, Hilton Head, S.C., June 1988.
- [5] Kimura, W.D. et al "Spark Columns in High power Preionization Triggered Switches," Final Report, STI Report C11.228.01, Submitted to Naval Surface Weapons Center, June 1985.
- [6] Bonacina, C., DelGiudice, S. and Comini, G., "Dropwise Evaporation," Journal of Heat Transfer, Vol. 101, p 441, 1979.