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THE DQ SWITCH

Operation at 4 Million Volts and 800 Kiloamperes

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1 December 1979

Final Report for Period 1 April 1979—1 December 1979

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Gas Switches	High Power Switches	
Spark Gaps	Casino	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the progress to date with high voltage gas switching using the DQ switch developed by Pulsar Associates, Incorporated. Self-breaking operation has been achieved at 4 million volts and 800 kiloamperes. Triggered operation has been achieved at 2 million volts. The control of insulator tracks is described, along with the engineering of the switch.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 Summary

The DQ switch is a gas insulated switch. In design, it is a column consisting of a series of spark gaps. It is intended to be used to switch water-insulated coaxial line systems, and in fact, is expected to replace water switches currently in use. More importantly, it will make possible the engineering of more effective high power systems in the future. Water switches have always been plagued by high command jitter and poor shot-to-shot reproducibility. Evidence continues to build up demonstrating that water dielectric switches operate with very high energy and power losses, up to 30 percent in high powered machines. There is reason to believe that the relative fraction of power lost does not decrease with increasing machine power, but instead stays relatively constant.[1] This does not argue well for the future if water switches had to be relied upon in this design.

Poor timing, ragged reproducibility and high energy and power losses inherent in water switches combine to impose severe inhibitions on the design of high power energy discharge systems. For example, it has proven to be very difficult in practice to routinely trigger several water switches simultaneously so that a number of different modules can be fired together. Modular design in high voltage pulse power introduces important economies of scale and high levels of performance which are not available from single-line machines. The TRESTLE and HPD EMP simulators are each two-module examples of what can be achieved in high voltage at somewhat lower power levels by simply bringing triggering up to modern standards. In both cases, reliability and performance have been dramatically improved by the addition of reliable low jitter triggering. The DQ switch will provide the key technology which will permit system designers to take advantage of these same benefits of modular design in the high power, low impedance designs required for effective radiation simulation.

The major objective for the 1979 DQ switch program was to demonstrate the practical feasibility of the switch design by overcoming the wall tracking difficulties of the switch insulators, and further, to demonstrate the feasibility of externally triggering a multimegavolt switch, using a relative low level (100 kV) trigger pulse. This objective has been met. The DQ switch has been operated in the self-breaking mode at record levels for a gas switch — four million volts hold off and a peak current of 800,000 amperes. Triggering was successfully accomplished at 2 MV with a jitter of less than ten nanoseconds. By the end of the reporting period (November 15, 1979), geometry changes in the trigger section were well under way which were intended to increase the triggering range and lower the timing jitter still further.

During this year, a new insulator design was developed out of extensive testing. The new design, with flanged ends, markedly inhibits the formation of interior wall tracks in the switch. These wall tracks, or low-power streamers, had been causing spurious triggering in all earlier tests.

The body of this report describes the DQ switch, its operations and the tests which were conducted at Casino during the latter part of 1979. It describes the tests which were done at Pulsar's Sorrento Valley plant in investigating the wall tracking problem and the steps that were taken to control interior insulator wall tracks of the switch. Finally, the triggering of the switch is described, and the steps that are being taken in preparation for the next set of tests to extend the DQ switch to multi-column and multi-module operation.

The work described here was sponsored and funded by the Defense Nuclear Agency, and included the close partnership and cooperation of the staff of the Casino facility at the Naval Surface Weapons Center (NSWC). The bibliography contains references to other reports published by the NSWC staff related to this work.[1, 2]

2.0 Description of the DQ Switch

The test configuration at Casino for the DQ switch is shown in Figure 1. The switch closes the gap between the pulse line and the pulse transformer. The trigger cable for the switch enters the system through the inductive support at the load side of the switch. In a typical test shot, the pulseline is charged to approximately four megavolts. When the switch fires, the output pulse is about 80 nS wide with a peak current of 800 kA. Figure 2 is an outline view of the DQ switch in the pulseline. The active length of the switch is 20.5 inches, including 18.8 inches of wall insulation. The "blow down" tank is a gas ballast volume which helps to flush the switch when pressure is dropped after each firing. Details of the interior of the switch can be seen in Figures 3 and 4, which show the trigger section, and Figure 5, which shows the middle sections of the switch. The full switch is shown in Figure 5.1.

The DQ switch operates as a set of spark gaps connected end to end in series. The number of series sections depends upon the voltage to be switched. In the tests described here, ten sections were used, each rated at 400 kilovolts, for a total of four megavolts. The gaps are insulated by pressurized gas. The volume of the dielectric gas has been kept deliberately small in order to reduce the danger of catastrophic blowup, which would be presented by the large amount of energy stored in a larger volume of compressed gas. Because the switch is gas insulated, no significant acoustic shock wave passes from the spark gaps to the water. This eliminates an important cause of mechanical strain and experimental noise in several existing large simulation machines.

The switch employs timed ultraviolet illumination in all sections. The trigger section at the top of the drawing is the first switch gap to close. Illumination in this section is provided by a special process described below. When the trigger section closes, it overvolts the second section, which is also illuminated

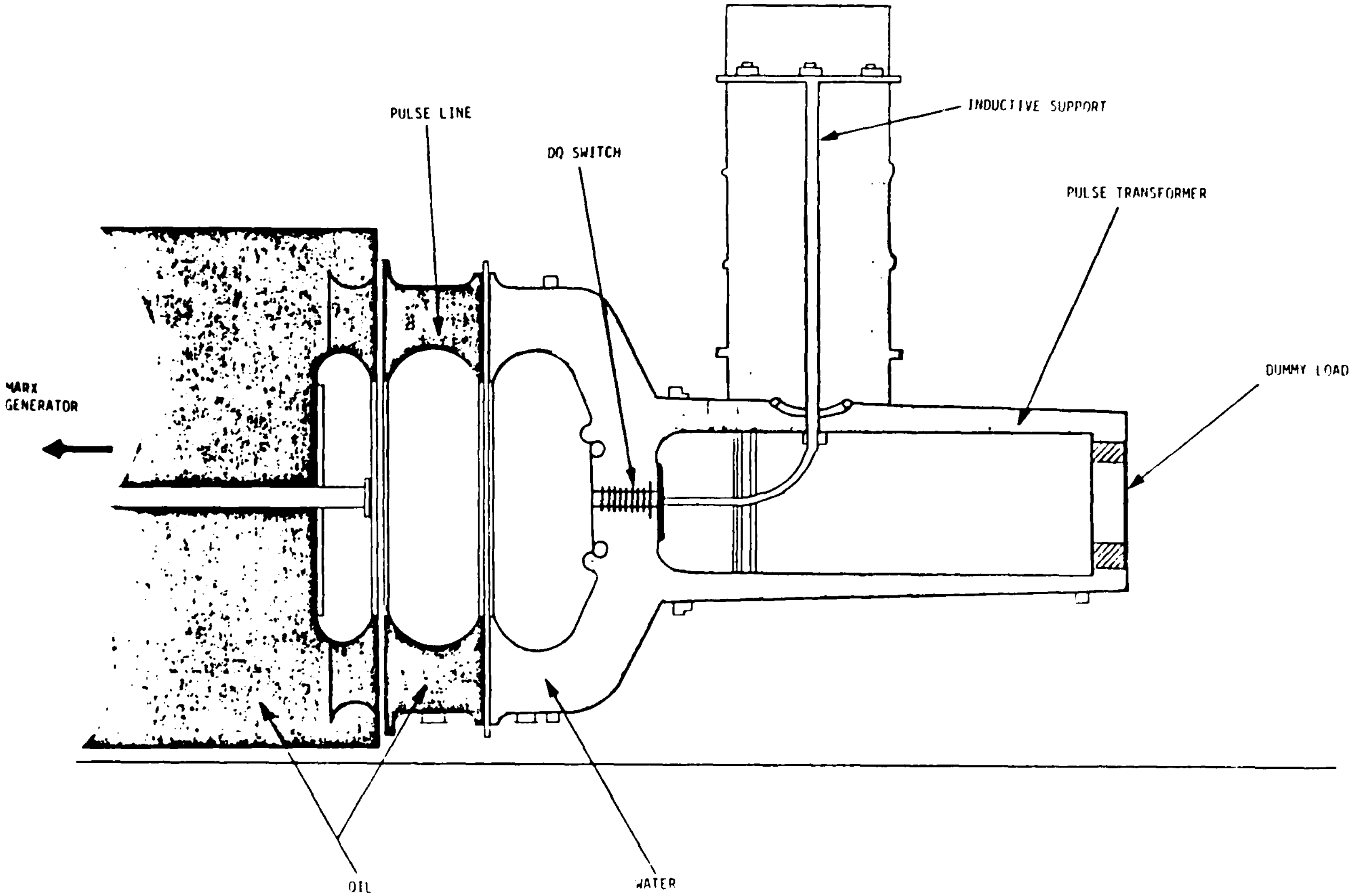


FIGURE 1   CASINO DQ TEST CONFIGURATION

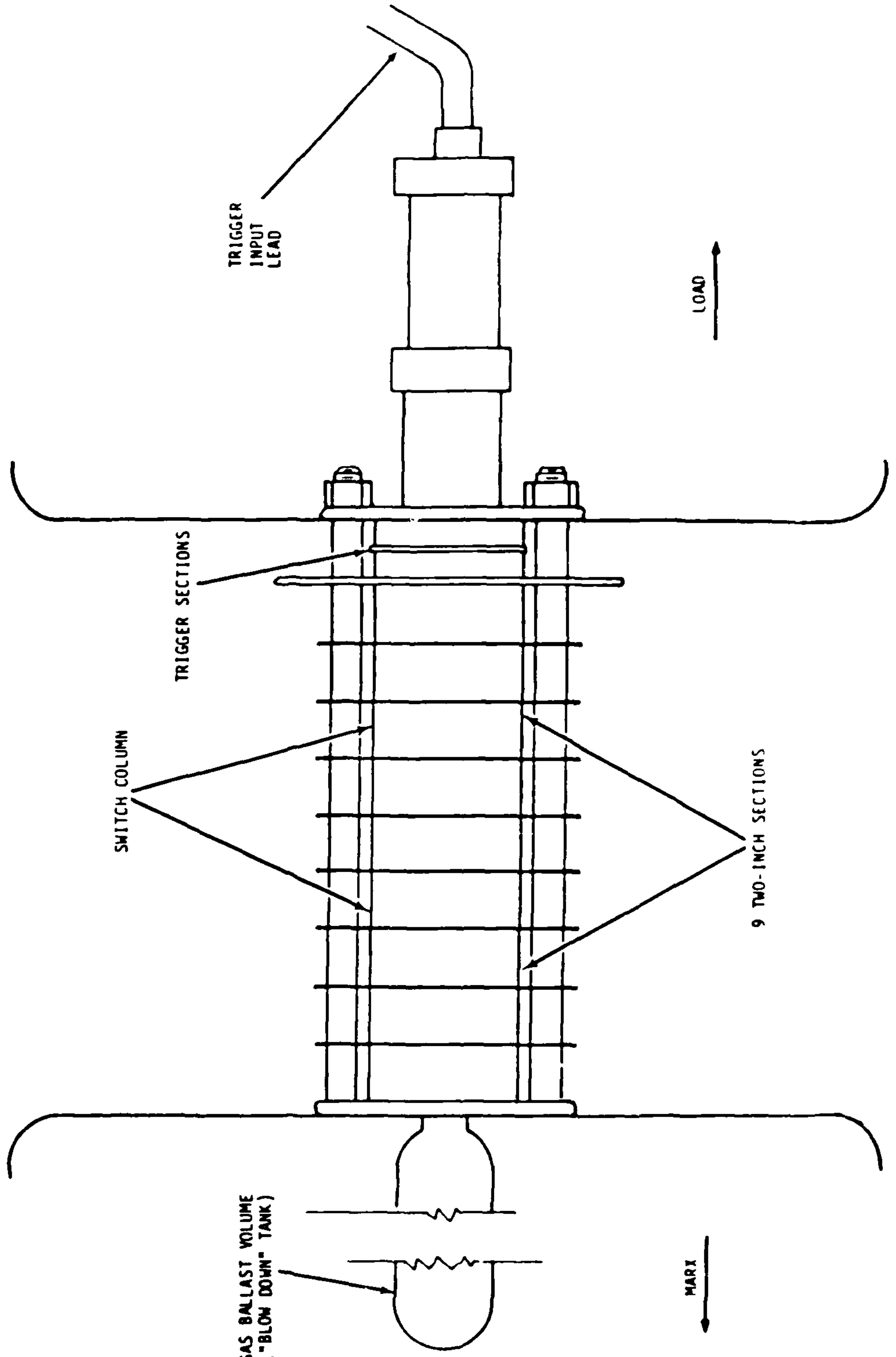


FIGURE 2 DQ SWITCH SIDE OUTLINE VIEW

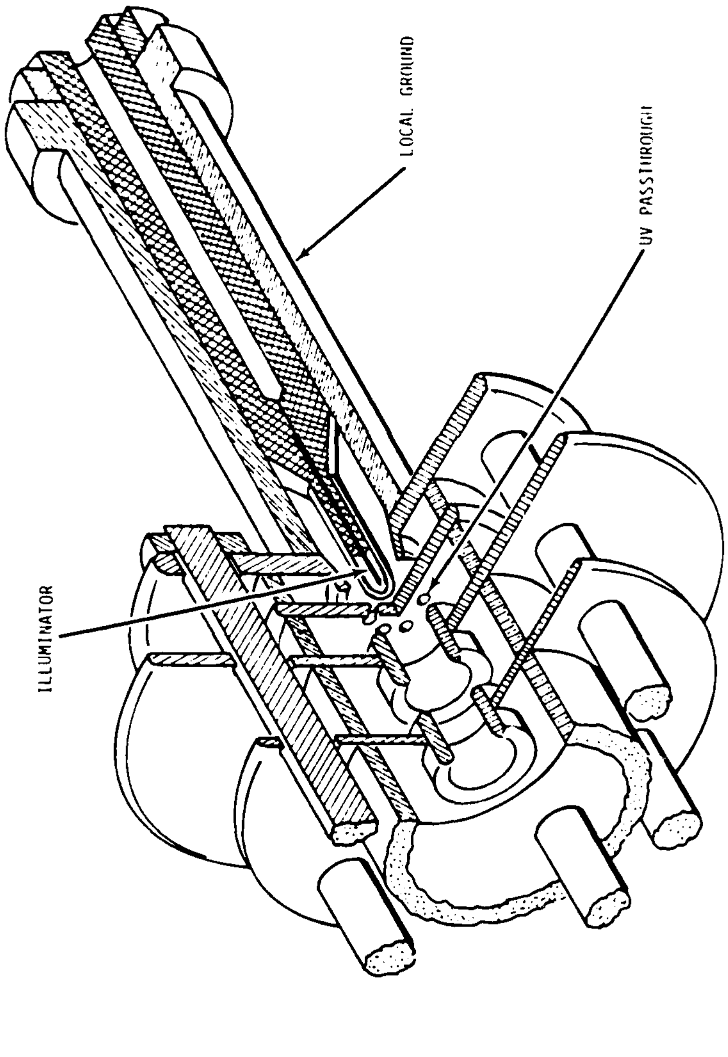


FIGURE 3 DPJ SWITCH TRIGGER SECTION

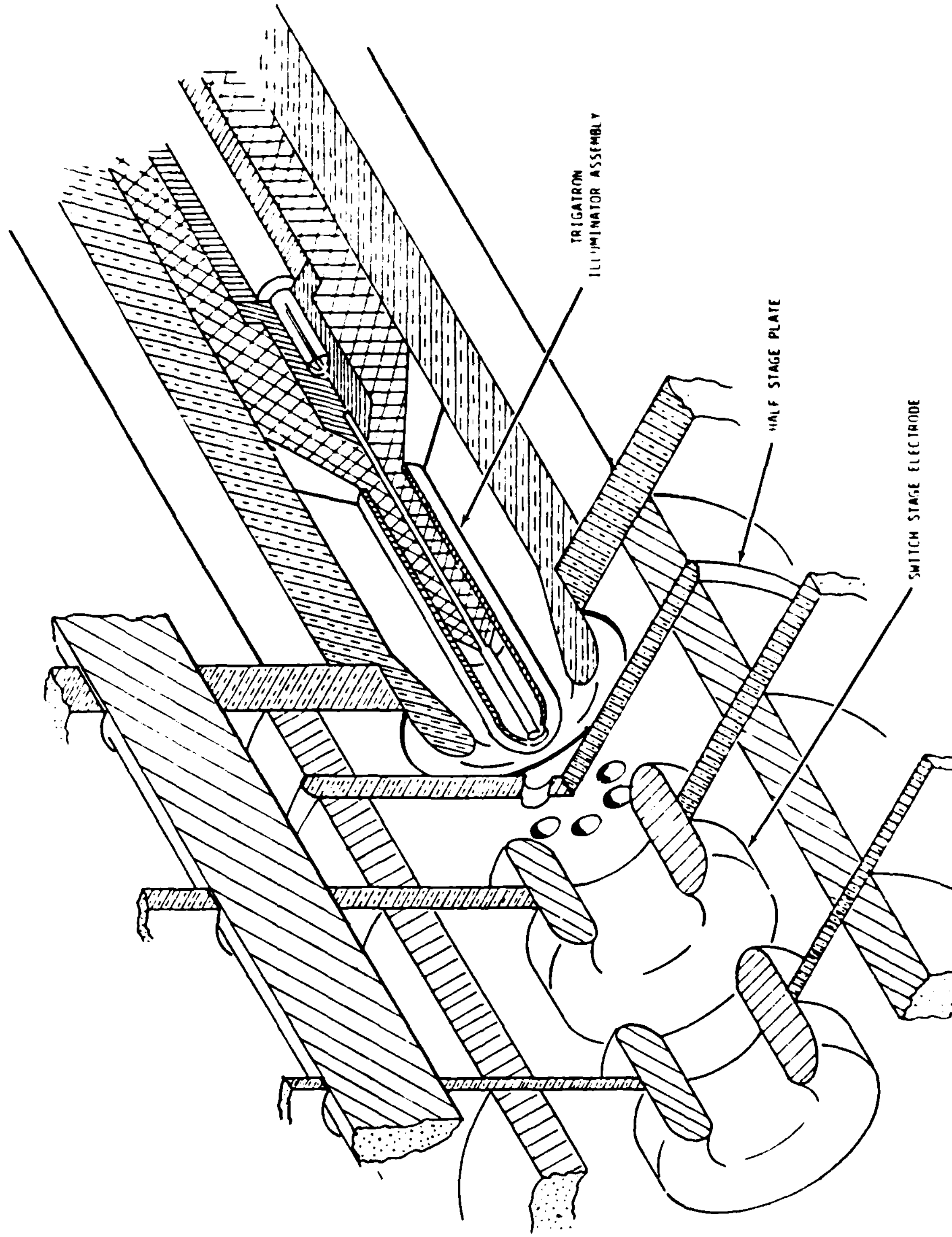


FIGURE 4 DQ SWITCH TRIGGER SECTION

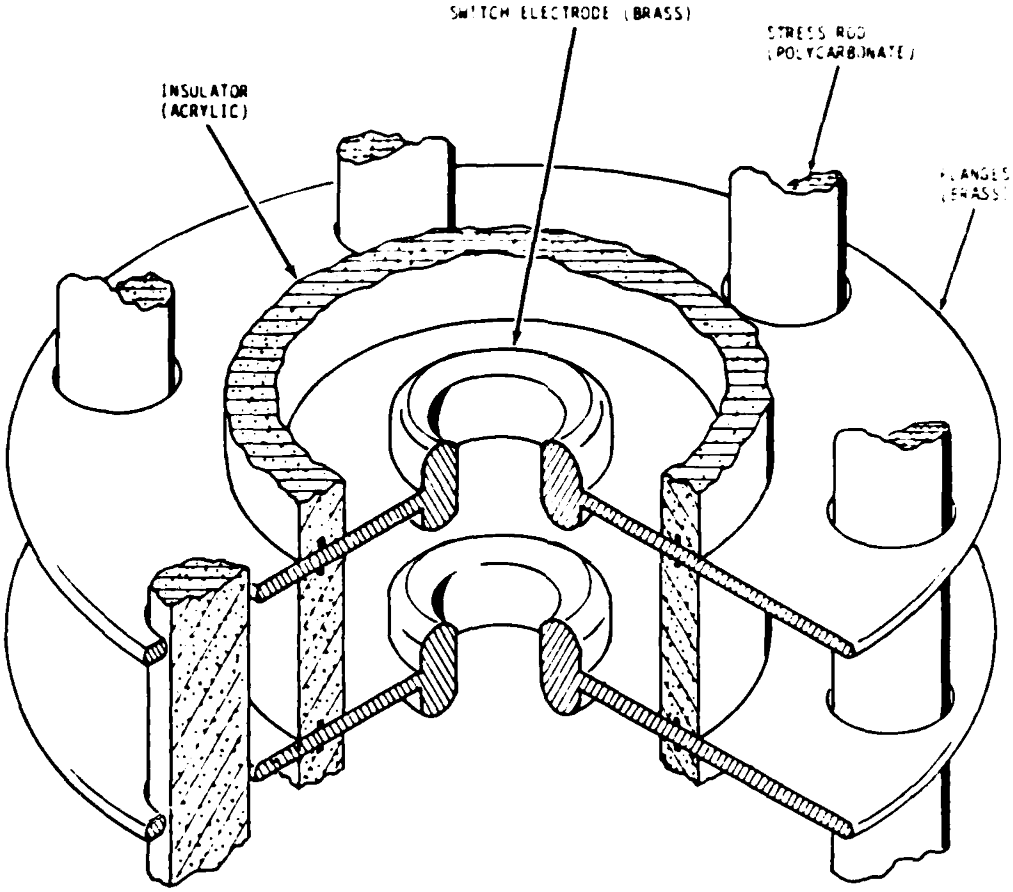


FIGURE 5
DQ SWITCH JULY 1978

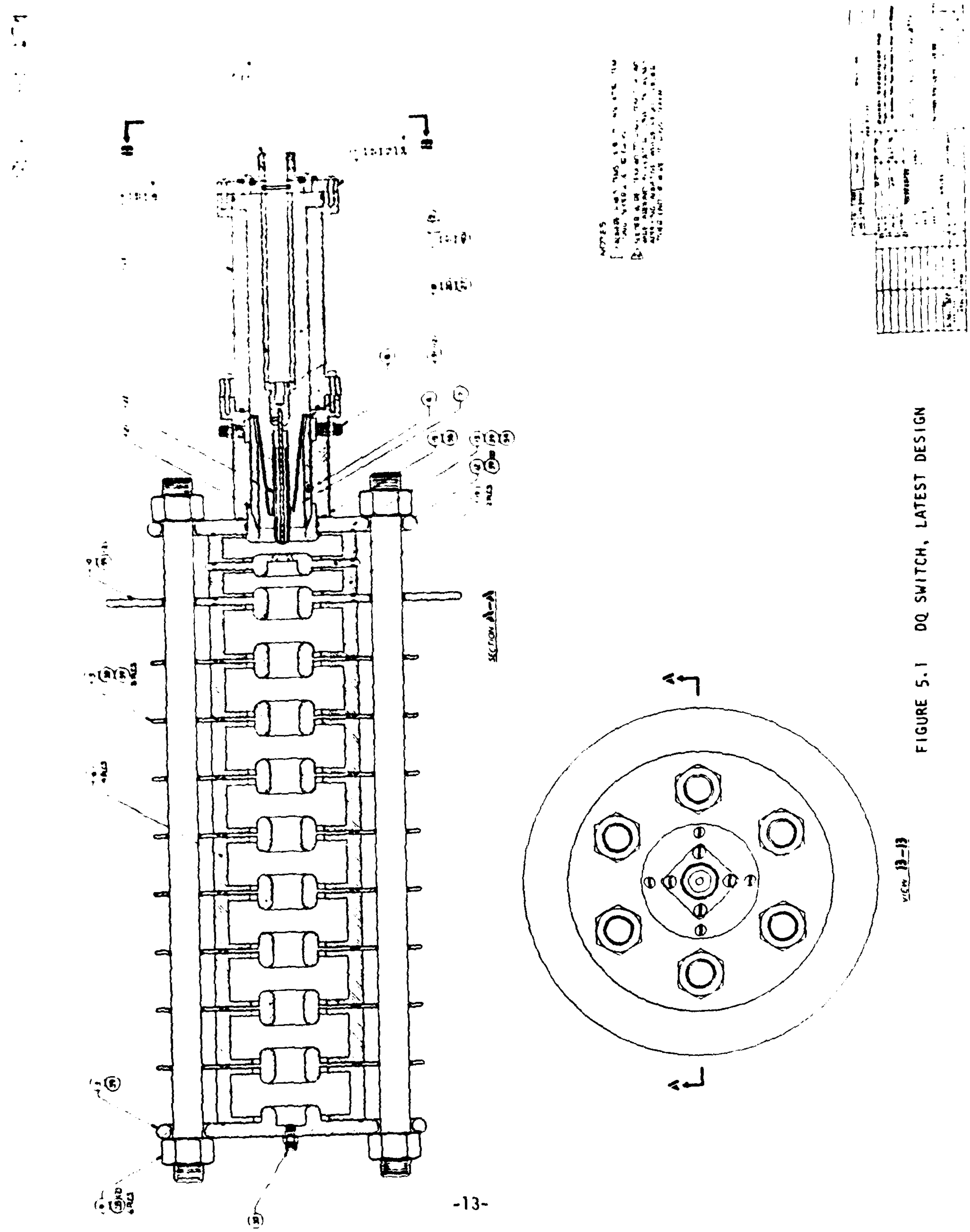


FIGURE 5.1 DQ SWITCH, LATEST DESIGN

by ultraviolet passing through the middle of the electrode from the trigger section spark and falling on the cathode of the second gap. Each subsequent section breaks down in turn, overvolted and illuminated by the preceding section. It is important to note that the switch must be triggered from the positive end, so that the ultraviolet falls on the cathode of the next section to fire.

One purpose of the use of individual series sections is to permit triggering of the switch with a voltage which is a relatively small fraction of the total voltage being held off. When triggering was used in these tests, a 100 kilovolt pulse from a PULSPAK 50Q was employed.

The trigger section of the DQ switch was developed at Pulsar under an internal R&D program. Its design has been carefully arranged so that at each stage in the breakdown of this key section, there is always adequate ultraviolet on the cathode of the subsection next to be overvolted. The operation of the trigger section is shown in Figures 6 through 9.

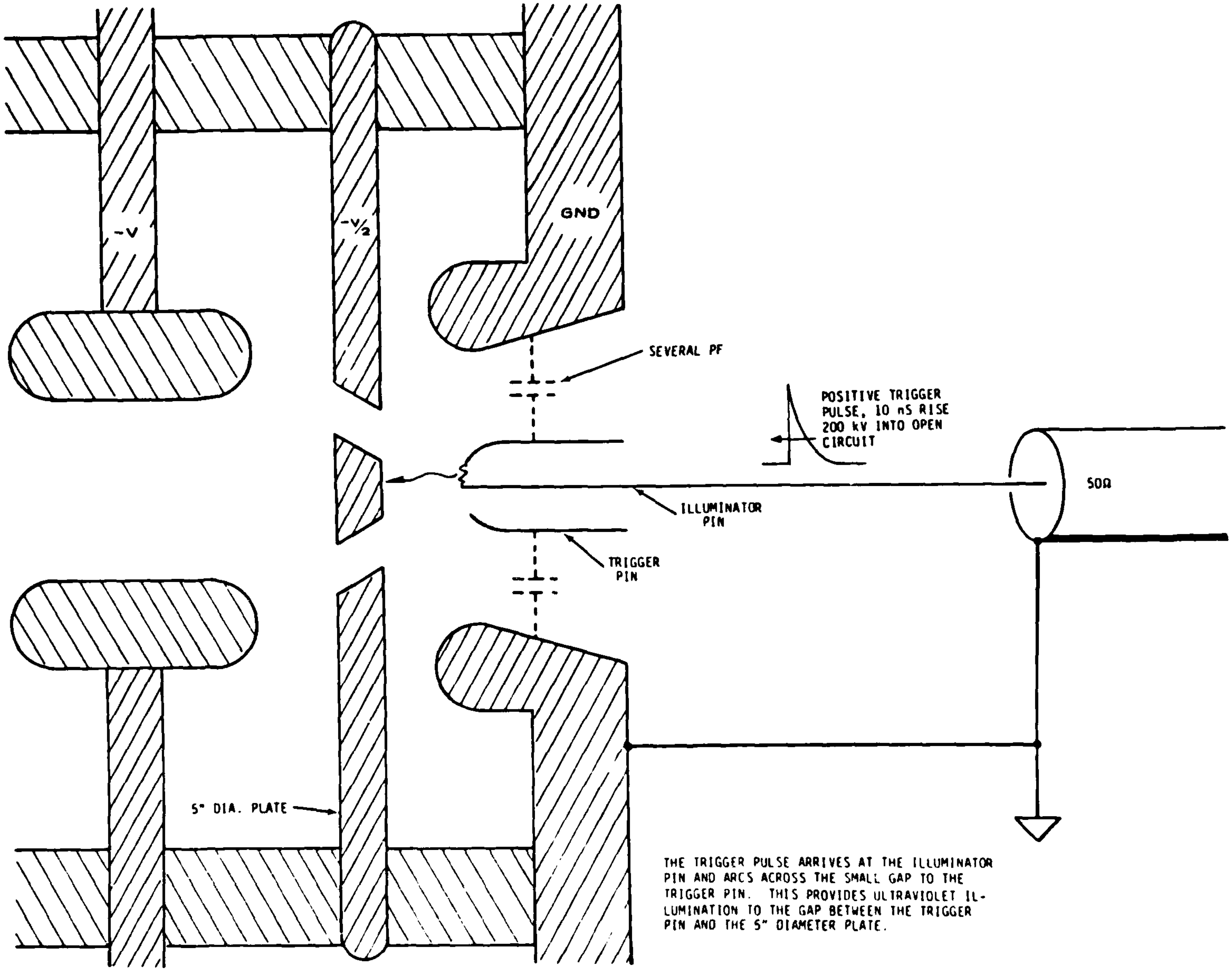


FIGURE 6 TRIGGER SECTION OPERATION

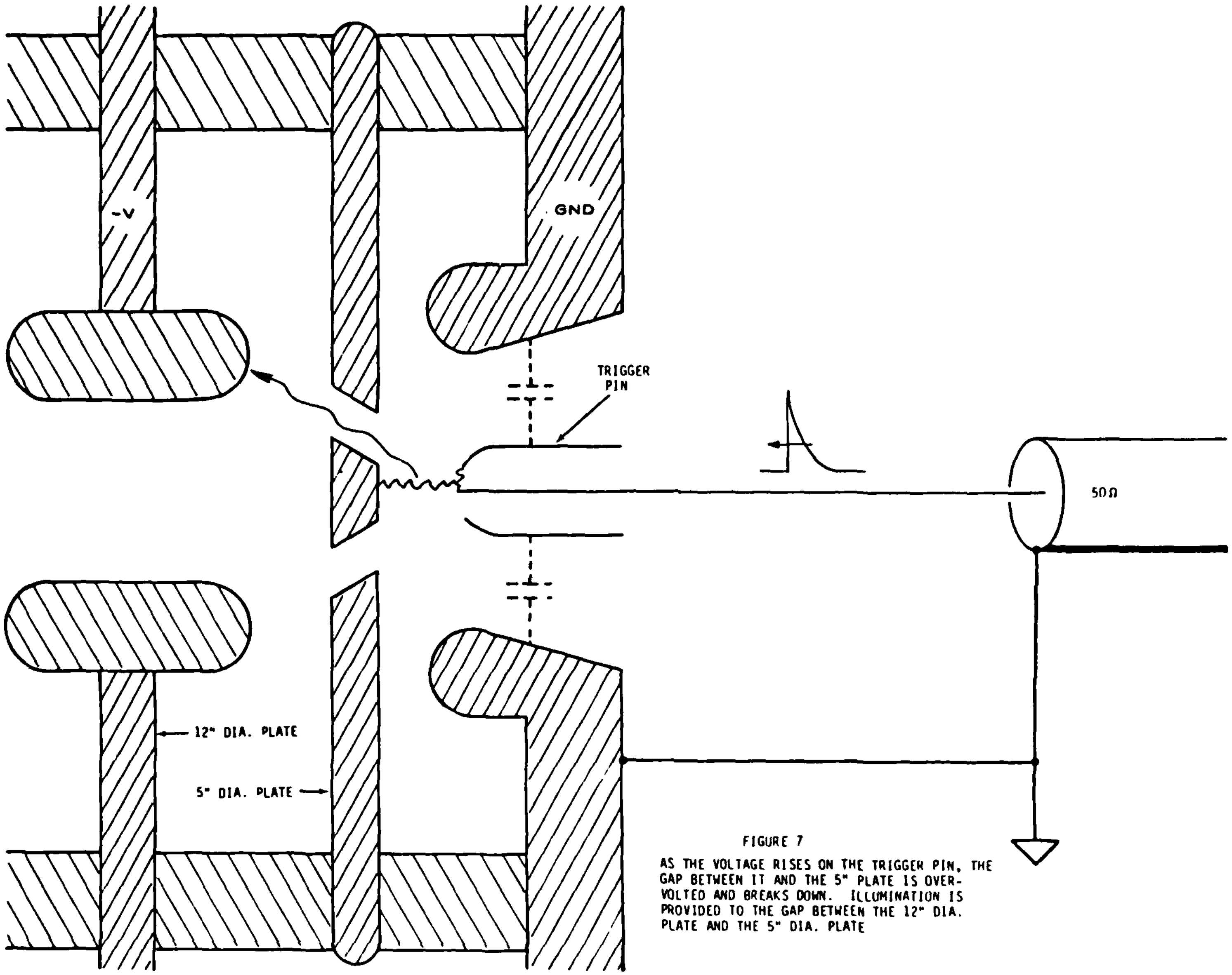


FIGURE 7

AS THE VOLTAGE RISES ON THE TRIGGER PIN, THE GAP BETWEEN IT AND THE 5" PLATE IS OVER-VOLTED AND BREAKS DOWN. ILLUMINATION IS PROVIDED TO THE GAP BETWEEN THE 12" DIA. PLATE AND THE 5" DIA. PLATE

FIGURE 7 TRIGGER SECTION OPERATION

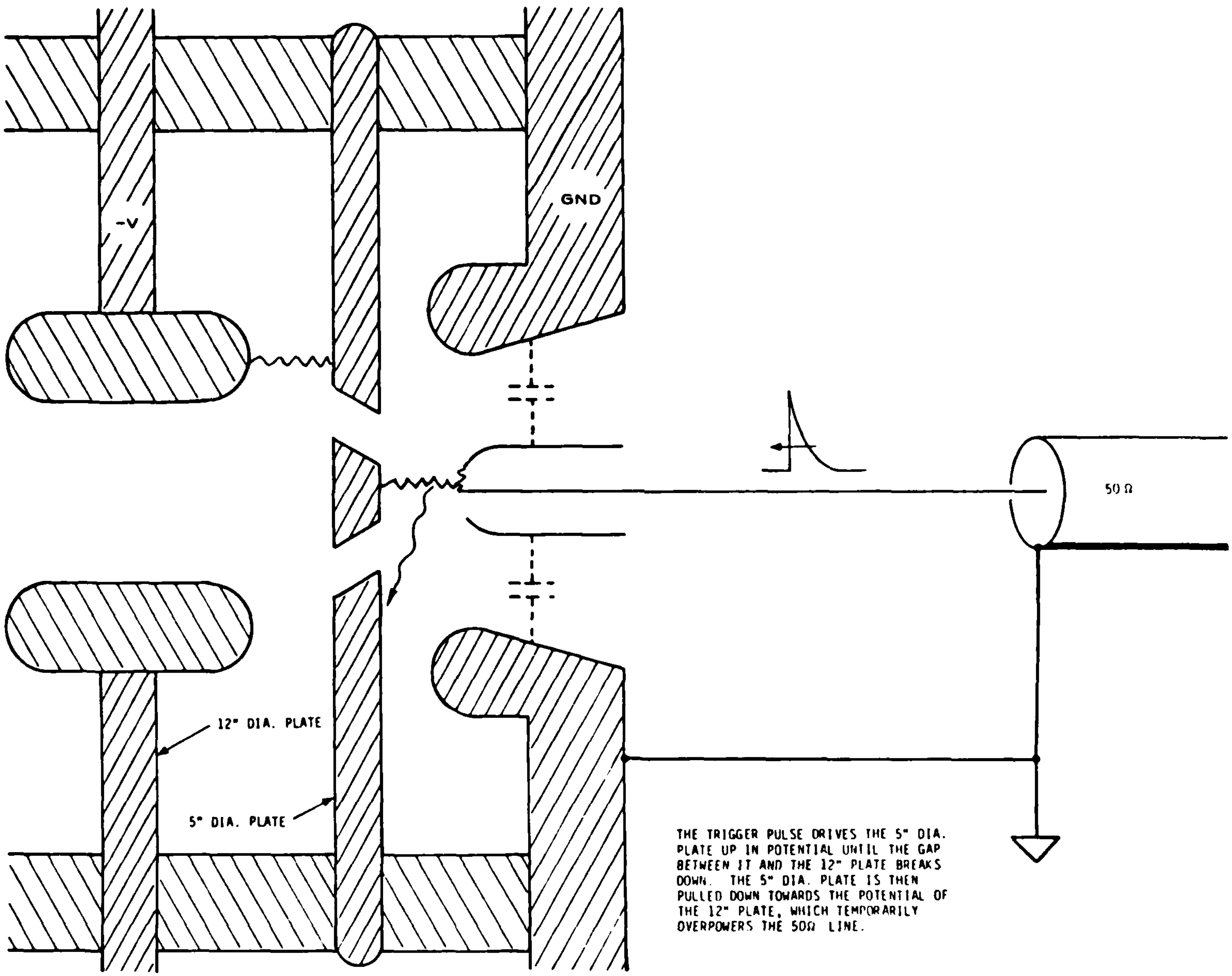


FIGURE 8 TRIGGER SECTION OPERATION

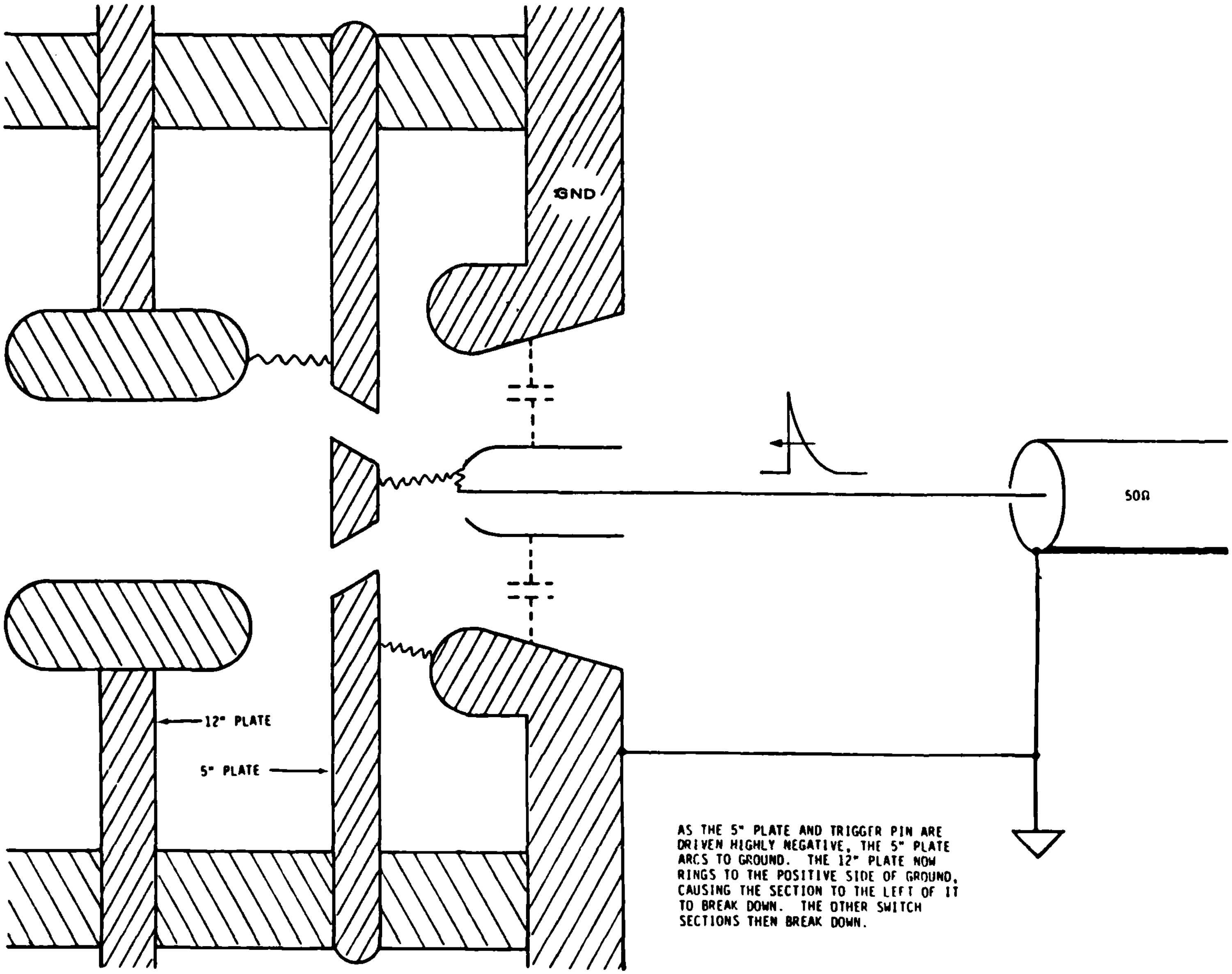


FIGURE 9 TRIGGER SECTION OPERATION

3.0 Spurious Breakdown — The Main Problem

The 1978 tests of the DQ switch showed that further progress would first require the elimination of the spurious breakdown of the switch above two million volts. The self-breakdown voltage varied so much from shot to shot that it was very difficult to reliably obtain a shot above two megavolts. This situation made testing of triggered operation virtually impossible because of the wide and uncertain timing intervals required. The 1978 region of breakdown using SF_6 is shown in Figure 10.

The spurious breakdowns were attributed to electrical streamers or insulator wall tracks upsetting the electrical grading of the switch, and thereby firing it. The general description of the insulator streamer is shown in Figure 10.1. It is important to note that these streamers usually left little or no trace, and very rarely damaged the insulator. Their effect was believed to be confined to upsetting the electric field gradients, causing the switch to fire.

The authors of this report feel that the good operating results achieved in 1979 resulted from the fact that a new insulator design was used which successfully inhibited the wall tracks. However, because of the discovery of an unambiguous "conditioning" effect in the switch this year, other workers[3] have pointed out justifiably that additional work will be needed to be absolutely certain that the effects of conditioning are separated from wall tracks. The conditioning phenomena is described further below.

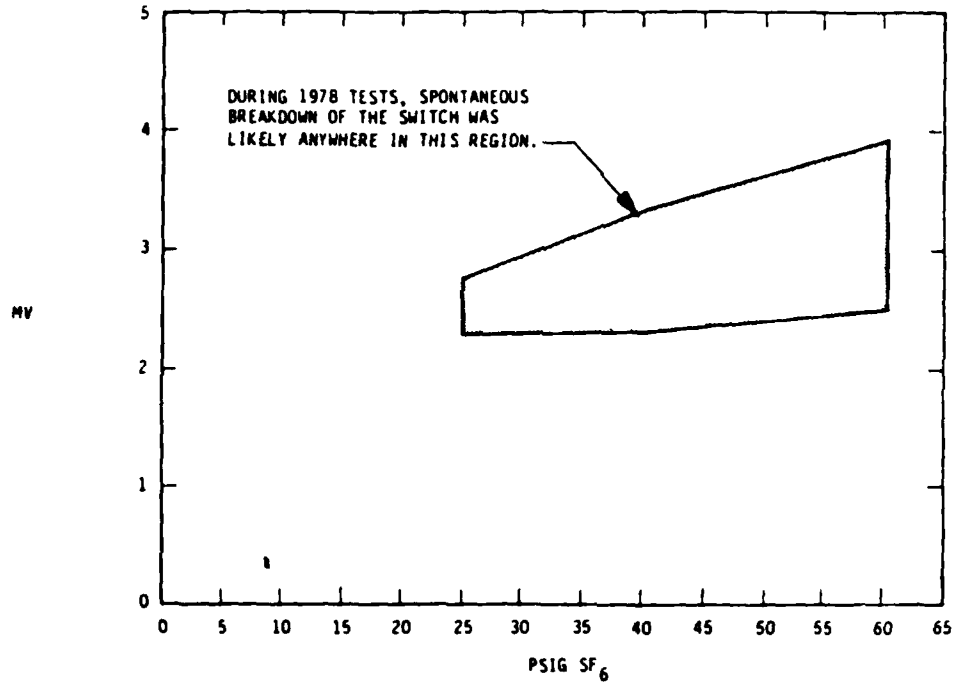


FIGURE 10 DQ SWITCH SELF-BREAK MODE OPERATING RANGE JULY 1978

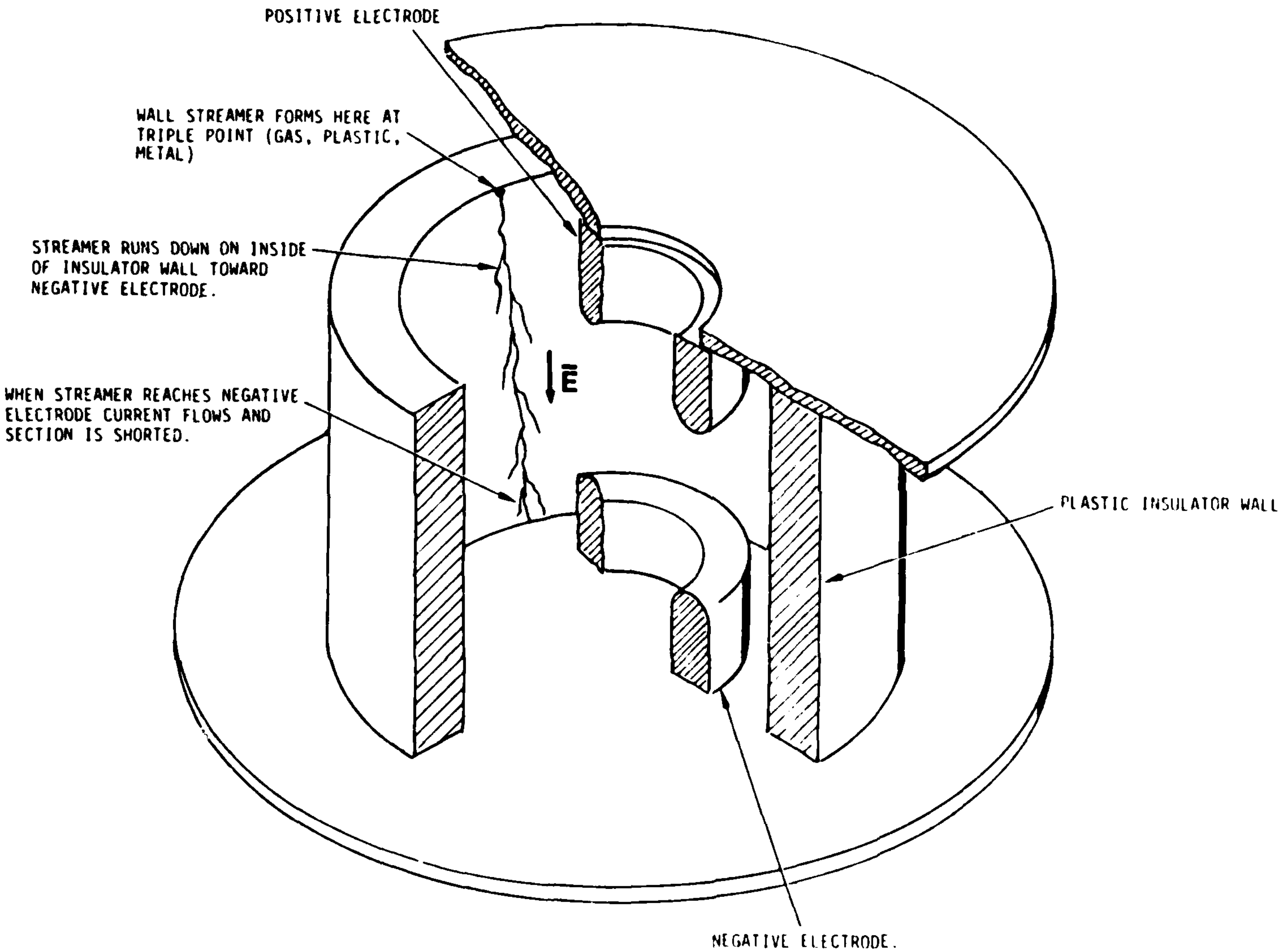


FIGURE 10.1
WALL STREAMER FORMATION INSIDE OF SWITCH SECTION

4.0 Single-Section Switch Tests

The experimental attack in 1979 was first sharply focused on the insulator design and solving the wall tracking problem. The work was intense but systematic. Arc marks had been observed on the inner wall surfaces of the DQ switch insulators, leading to the hypothesis that the erratic self-break shots were due to some anomalous insulator behavior. A series of tests were then undertaken in order to determine how the insulators could be improved. In the descriptions below, acrylic was used as the insulator material unless otherwise stated.

The set-up used for testing the insulator sections is shown in Figure 11. Figure 12 is a block diagram of the diagnostics. The test stand had a peak output of 450 kV with a 1.5 microsecond risetime. For the single-section tests, 1977-type switch insulator sections were used. These sections were only half the size of the present DQ insulators, so they represented a 50 percent scale model. The outside insulator diameter was 2.4 inches, instead of the five inches of the large version used at Casino. The length for the small insulators was one inch, compared to the larger type's two inches. At a typical peak operating voltage of 300 kV, a waveform of approximately 60 kA peak current oscillated in the DQ switch section immediately after breakdown.

An initial series of tests (May, 1979) suggested that placing O-rings in the electrode plates was better for switch self-break scatter than having them in the insulator walls (see Figure 5 for O-rings in insulator configuration). The electrode plates used in the small switch test station were, therefore, machined to accept O-rings, and future insulators were made without them. Later switch tests, comparing O-ring grooves in the insulator and ungrooved electrode plates, did not give quite so clear results, so that there now may be some ambiguity as to which is better, if either. At present, the O-ring grooves will be left in the metal in the future because of reliability concerns.

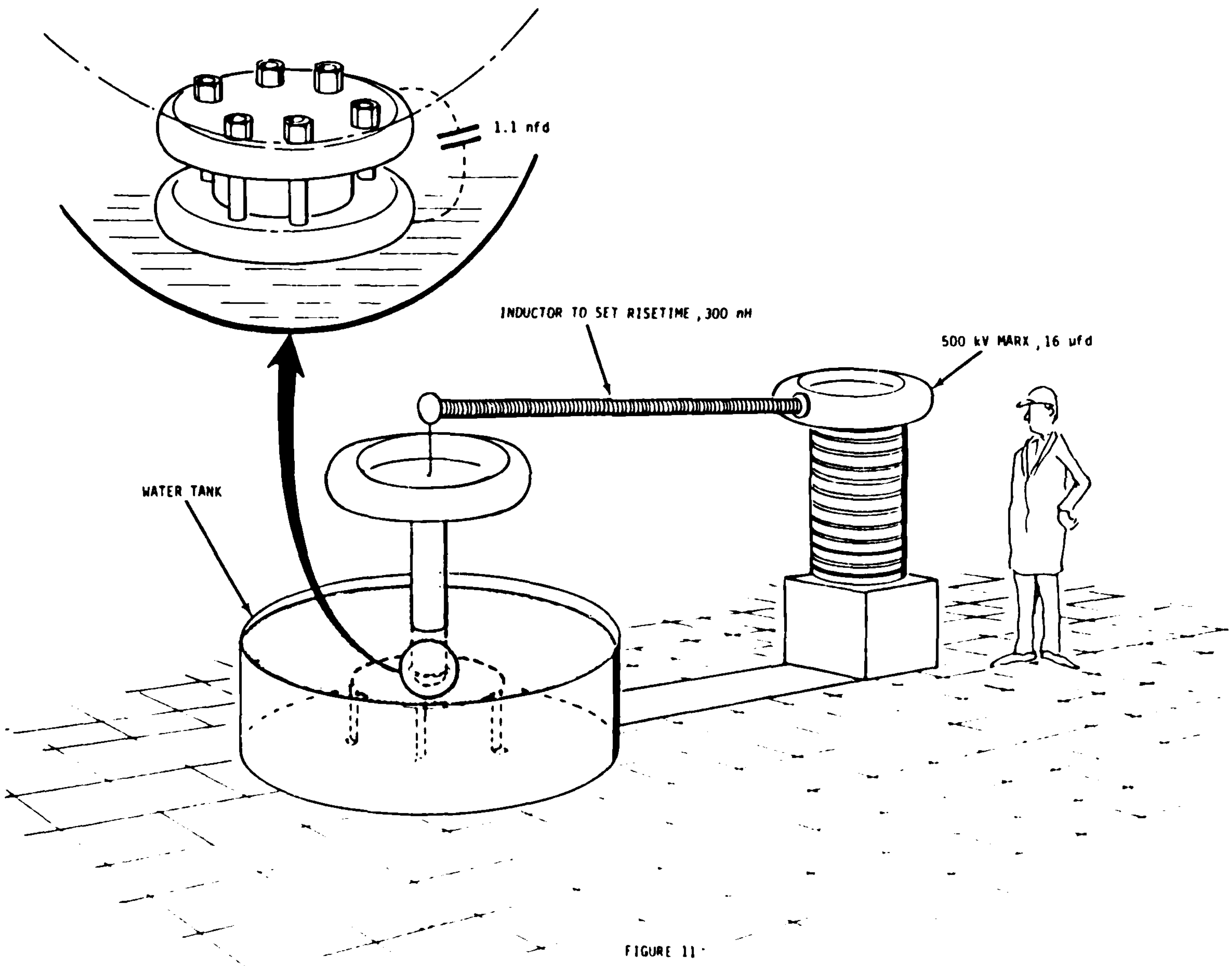


FIGURE 11
DO SWITCH TEST STAND

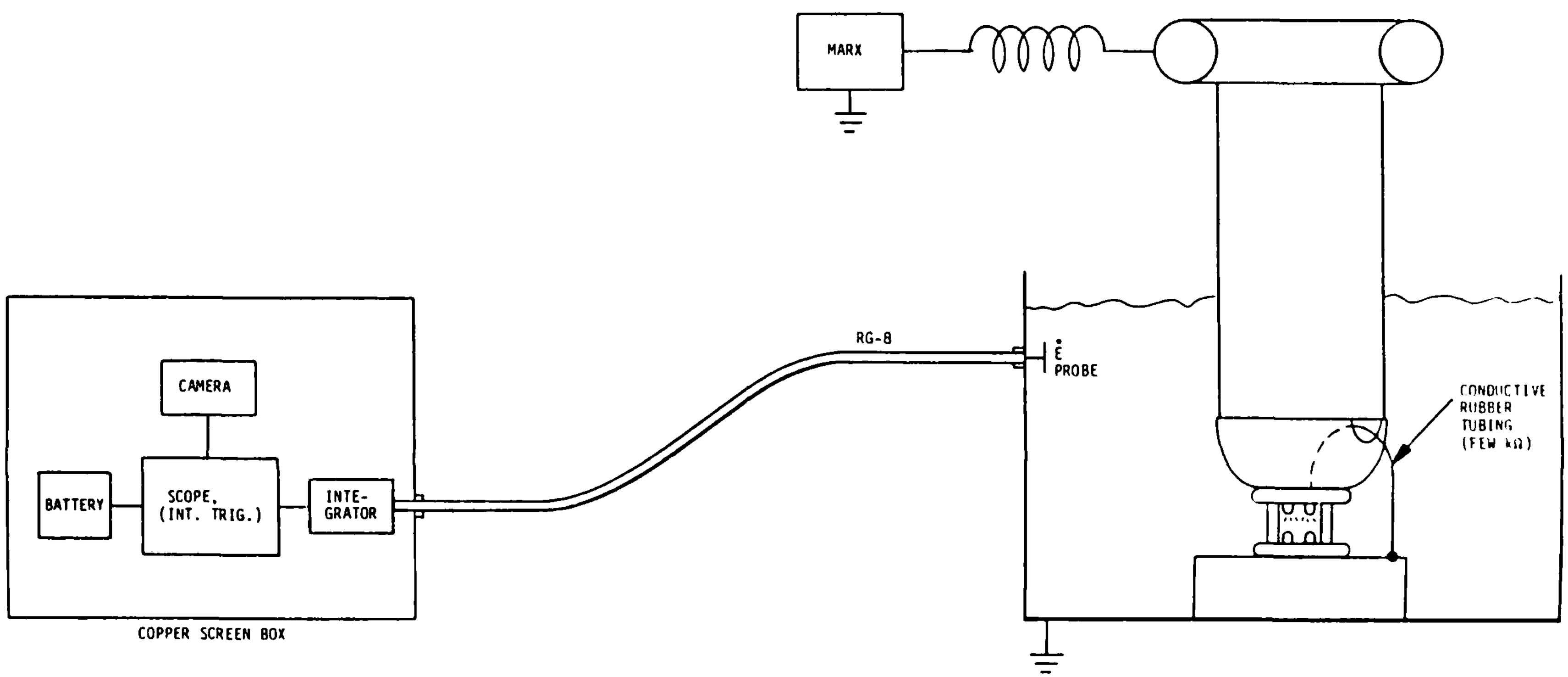
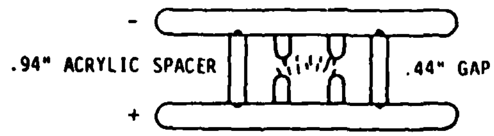


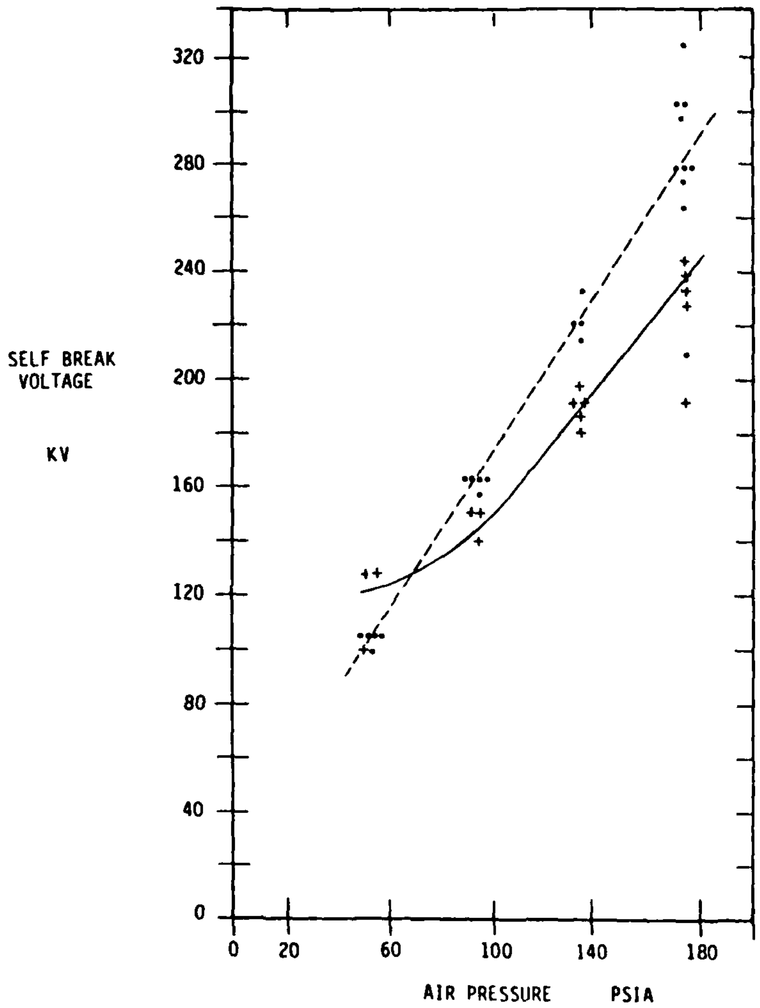
FIGURE 12 TEST STAND DIAGNOSTICS

The results with the O-ring groove and other experience at the Sandia Laboratories[4] on similar insulator geometries suggested that the electric fields at the junction of the insulator and the electrode geometry played a critical role. As a result, cylindrically symmetric insulators with the inside walls tapered to an angle 19° from the vertical were tried. No reliable improvement was noted with the insulators in either polarity.

However, a different test revealed a most striking effect concerning the effects of UV illumination. This concerned the behavior of the self-break curve for straight-walled insulators when UV illumination was removed. Instead of a slight increase in the apparent self-break voltage when UV was removed from the interior of the test switch, as one might expect to result from a small increase in the breakdown time delay, exactly the opposite effect was observed at higher voltages. The crossover point appeared to be at 65 psig and 140 kV. Figures 13 and 14 show typical examples of the effect. Note that although the absolute values of the two illuminated curves vary slightly due to calibration errors, the fractional difference between the illuminated and nonilluminated curves increases at a fairly continuous rate (see Figure 15).

It was hypothesized that the nonilluminated gaps' lower self-break voltage was due to the formation of unstable wall discharges on the inside of the insulator. In the absence of UV, the insulator surfaces conducted only with great difficulty. It was speculated that charge from the electrodes would pile up near the triple point until the local field was sufficient to allow individual streamers to break away, in a type of Taylor instability. By way of contrast, when UV is present, the insulator walls conduct slightly. In this case, charge cannot build up in non-uniform bunches on the walls. Instead, as the applied electric field increases, a small amount of current flows on the inside of the wall in a uniform manner. Such a uniform flow would not upset the field gradient of the switch and fire it. No attempt was made to determine a minimum illumination current needed to prevent wall discharges from reducing the self-break voltage of the switch. The illuminator

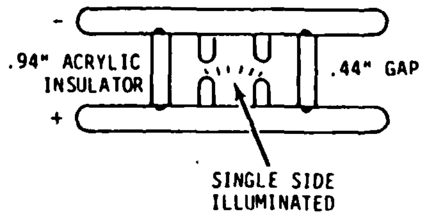


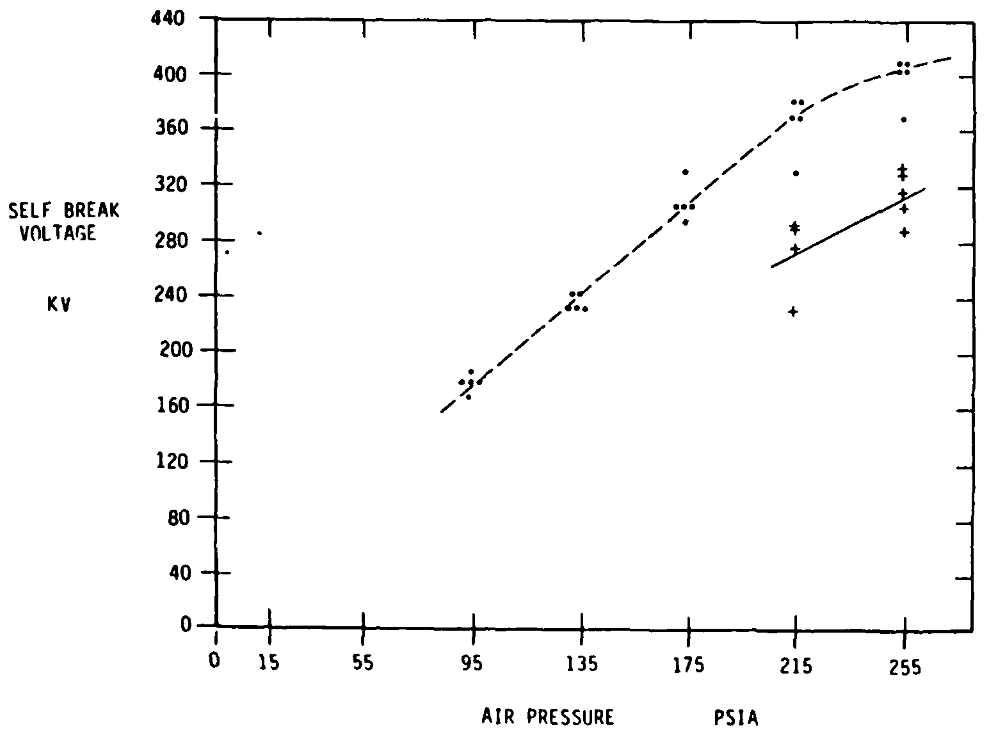


NOTE: NO WALL TRACKS SEEN ON INSIDE OF INSULATOR.

• ILLUMINATED BOTH SIDES — —
+ NON-ILLUMINATED ——

FIGURE 13 6/26/79 TESTS





NOTE: NO WALL TRACKS WERE OBSERVED ON INSIDE OF INSULATOR SURFACE.

• ILLUMINATED ---
+ NON-ILLUMINATED ——

FIGURE 14 6/29/79 TESTS

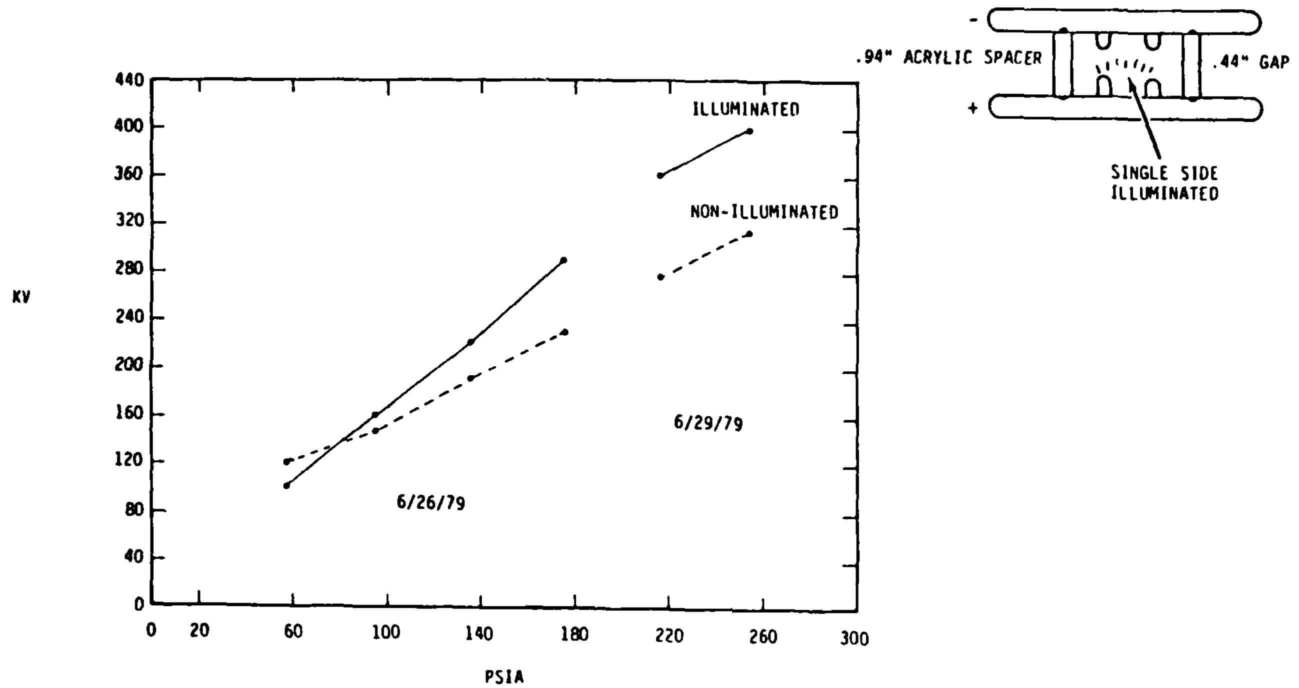


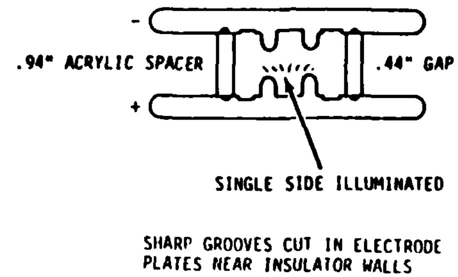
FIGURE 15 MEAN SELF-BREAKDOWN VOLTAGE VRS. PRESSURE 6/26/79 AND 6/29/79 DATA

gap that was used was current-limited by several kilohms in series with the voltage across the switch, yielding an illumination current of approximately 100 amps. The illuminator gap was only 0.01 inch across at the most, and was mounted in the anode electrode, so that the UV radiation would fall on the cathode as well as the walls.

An attempt was made to imitate the UV conduction effect by finding semiconducting materials that could be used as insulator walls so as to provide the necessary smoothed charge distribution by conduction electrons rather than by photoelectrons. Due to the high impedance of the Marx circuit, the needed material had to be resistive enough so that the wall currents would be limited to about 100 amps. One candidate material that was found and tried was a graphite-impregnated teflon. Direct measurement with a low voltage ohmeter indicated resistivity of approximately 10^4 ohm-cm. Unfortunately, this value dropped to roughly one ohm-cm at a few tens of kilovolts. Because of the difficulty of finding suitable materials which would be stable over these extreme voltage ranges, this approach was dropped for the time being.

Instead, a different approach was tried to obtain wall conduction. Sharp-edged grooves were cut into the electrode plates in close proximity to the insulator walls. This provided a sharp circumferential metallic edge which would generate corona near the insulator triple point (see Figure 16). The result was a significant decrease in the self-break voltage of the nonilluminated gap, as well as a widening of the scatter for both illuminated and nonilluminated configurations.

Next, it was decided to make it more unlikely for unstable streamers to get fully developed by shortening the absolute length of the insulator. A test switch section was constructed, utilizing an insulator wall consisting of three shorter pieces replacing the single longer one. Only illuminated tests were run. Results were rather poor with a fairly high self-break scatter (Figure 17). Because of the geometry of the switch, the two insulator sections closest to the anode were



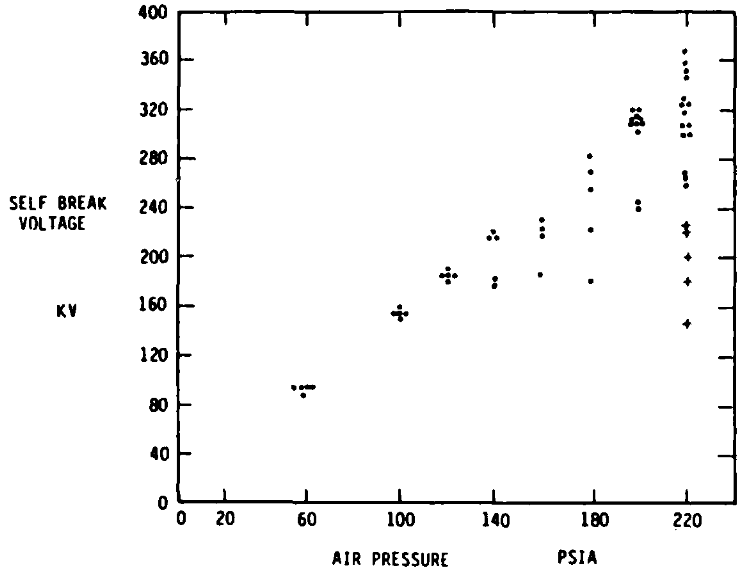
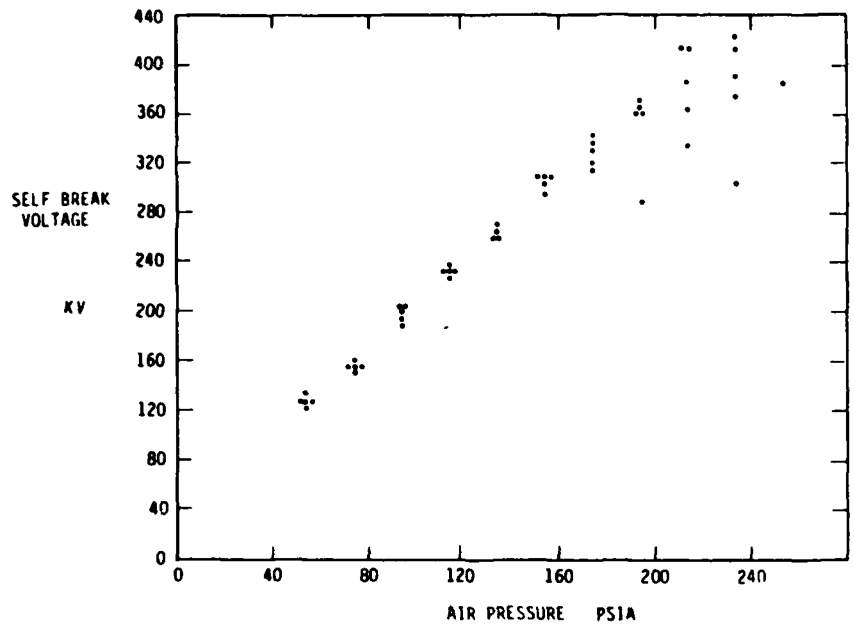
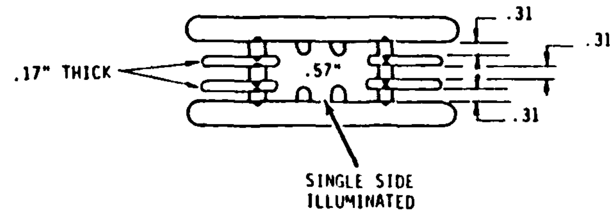


FIGURE 16 7/6/79 TESTS





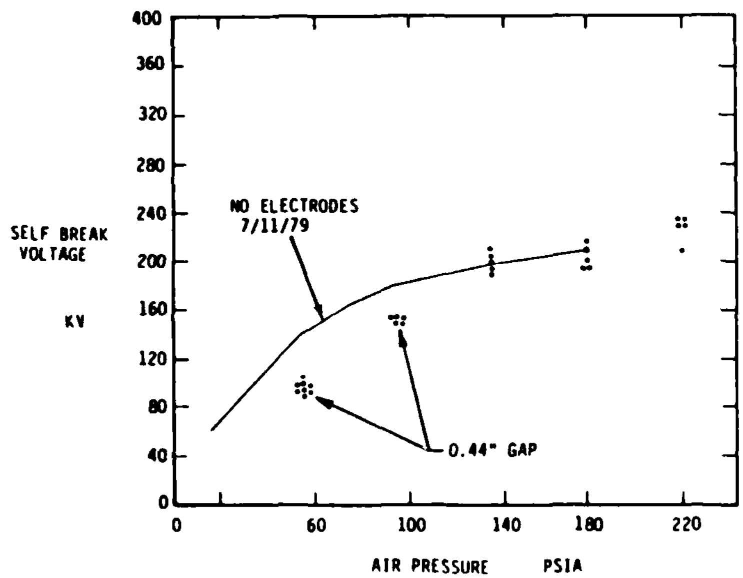
NOTE: WALL TRACKS WERE OBSERVED ON INSIDE OF ALL 3 INSULATORS, BURN MARKS WERE SEEN ON GRADING RINGS NEAR INSULATOR.

FIGURE 17 7/3/79 TESTS

not illuminated; and, therefore, it was believed likely that the switch was effectively nonilluminated. Wall tracks were seen on each of the three insulators. The poor results, coupled with the increased complexity, caused this approach to be abandoned.

Other passive approaches to slow the formation of streamer instabilities were tried. It was suggested that if the insulator surface were rough enough, then the charge might spread out in an analogy to wetting. In this direction, the inner insulator walls were abraded with #120 sandpaper. Little improvement was noted, and the walls tended to self-polish with repeated firings. In an alternative approach, the walls were covered with epoxy, and then coated with a layer of #30 silica sand. With the sand, the switch was operated both with the standard 0.44 inch electrode gap and without any electrodes at all. Without electrodes, the insulator was between two parallel plates. The results of the silica sand tests are shown in Figure 18. Note that both with and without electrodes, the switch tended to operate like a gas spark gap up to approximately 120 psia and 200 kV. Above this point, the self-breakdown voltage varied little with pressure, indicating that the electrode gap was no longer the determining influence, but that the discharge was going down the insulator wall in all cases. While these tests with rough insulator walls failed to show any improved performance, they did show that with the small insulators, it did not matter, up to 200 kV per section, how rough the walls were. If the wall track phenomena is electric field dependent, then from this data, the full size DQ insulator section should always take up to 400 kV, and the full switch up to four megavolts, even with the worst possible insulator damage simulated. Because the DQ switch in 1978 had trouble above two megavolts, it would tend to show that the condition of the insulator surface does not have a strong impact on switch breakdown.

In addition to the insulators, the switch gas itself has been suggested as a source of impurities which might interfere with switch operation. In order to determine the difference between replacing the switch gas after each shot and not



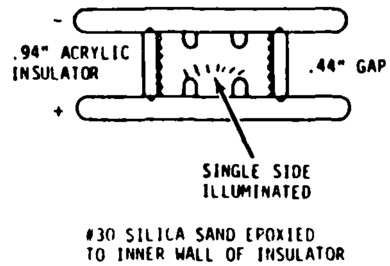


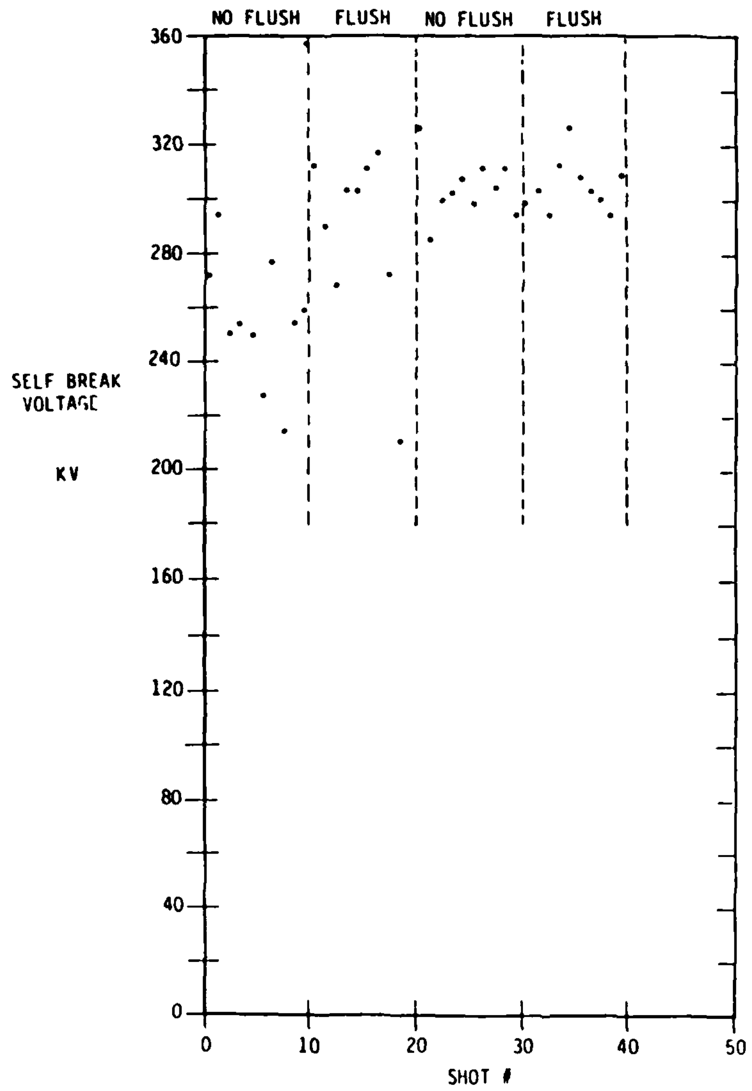
FIGURE 18 7/9/79 TESTS

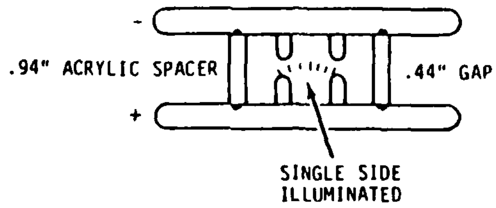
doing so, the test sequence reported in Figure 19 was conducted. There was apparently no effect, due to gas changes, on the self-break voltage for the number of shots made. The only noticeable effect on the switch was a narrowing of self-break scatter over time. Note that, in all of the other tests discussed here, the switch was flushed with new gas after every shot, unless otherwise indicated.

The standard gap in the half-sized DQ switch was 0.44 inches. However, two other sized electrode gaps were tested with the same straight-walled insulators, a 0.66 inch gap and a 0.22 inch gap. The voltage difference between the illuminated and nonilluminated self-break curves for the 0.66 inch gap was roughly half that of the 0.44 inch gap; however, it had a tendency to track down the inside walls. Not surprising, because the longer gap was approaching 70 percent of the insulator length. The 0.22 inch gap had a rather high scatter above 140 kV, and required 300 psia to reach 200 kV.

At this point in the work, it had been shown that intense UV falling on the insulators helped to suppress wall tracking, but a major practical problem remained. This was the lack of any simple means of providing adequate UV to switch sections beyond the trigger section in the full ten-section switch. Any solution to the wall track problem had to be practical from an engineering standpoint, and useful for the full switch assembly.

Passive measures had been considered. One approach was to attempt to physically block streamer travel as shown in Figure 20. This approach has been tried by other groups[4], and was tried with the DQ switch by the Casino staff. Contrary to our earlier expectations, it has always proved to be ineffective. Apparently, the energy of the streamer, once started, *is just too great. After a* very few shots, the barriers are simply blown off or tunneled through.





TEST SEQUENCE OF 6/21/79
ALTERNATING SEQUENCES OF FLUSH AFTER EACH SHOT AND NOT, 10 SHOTS/SEQUENCE.

SWITCH PRESSURE: 185 PSIG

SWITCH GAS: AIR

FIGURE 19 6/21/79 TESTS

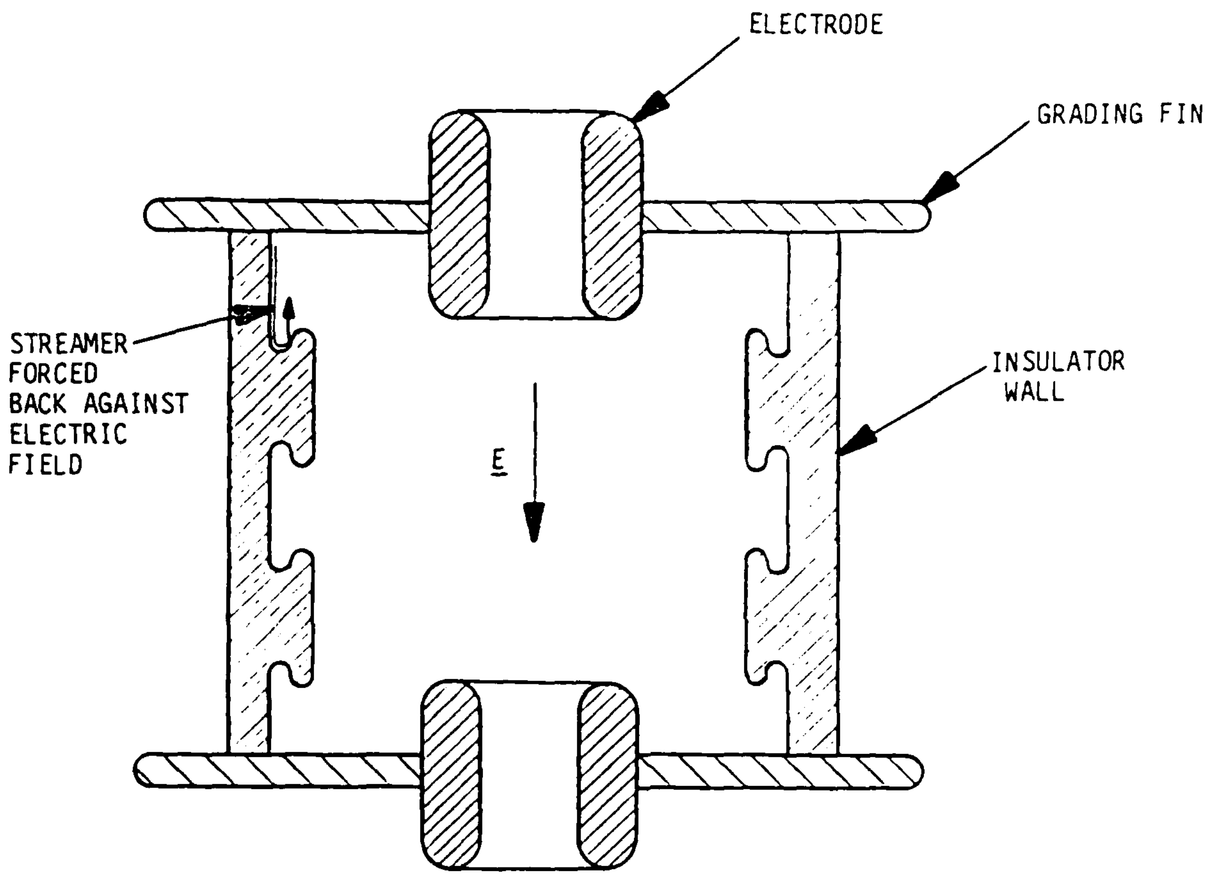


FIGURE 20

CONVOLUTED INTERIOR INSULATOR WALLS
TO CONTROL TRACKING.

THIS APPROACH WAS NOT SUCCESSFUL.

In an attempt to finesse these difficulties, a different electrode geometry was used. This consisted of fashioning the insulators with folded-in or "pill box" end flanges, as shown in Figure 21. This had the advantage of shielding the streamer launching point, the triple point of the insulator. This is the line where the electrode, the insulator and the switch gas meet. The triple point was shielded in the electric "shadow" of the switch electrode. Another advantage with this geometry was that after the streamer was launched, it still had to run radially during its early life perpendicular to the field. This presumably slowed down its speed and lengthened the time required for it to close to the opposite electrode.

The confirmation that the folded insulator was an improvement was that when it was tested, the self-break voltage for both illuminated and nonilluminated gaps was the same. This is shown in Figure 22. A comparison among various types of switches in their ratios of illuminated self-break voltage to nonilluminated self-break voltage is shown in Figure 23. This ratio should be close to one if there is no wall tracking. It should be noted that in addition to acrylic, folded insulators were tried made out of teflon (TFE), PVC and natural acetal. No difference in self-breakdown voltage was discovered among the different types.

Mechanical strength of the insulators is always a practical concern. In the test stand, at close to 400 kV on the insulator, double the intended rating, there existed a small possibility (few percent) of a water spark occurring on the outside of the switch. Acrylic insulators shattered when this happened. TFE held together, but tracked and shorted, while with PVC and acetal, no water spark occurred. Even if there had been a spark, it was believed that PVC and acetal would be much more resistant to shattering. For this reason, PVC and acetal were introduced as candidate insulator materials for the full-size switch.

Another mechanical point of concern is the insulator flanges. The inside corners (between the flanges and the walls) of the folded insulator are

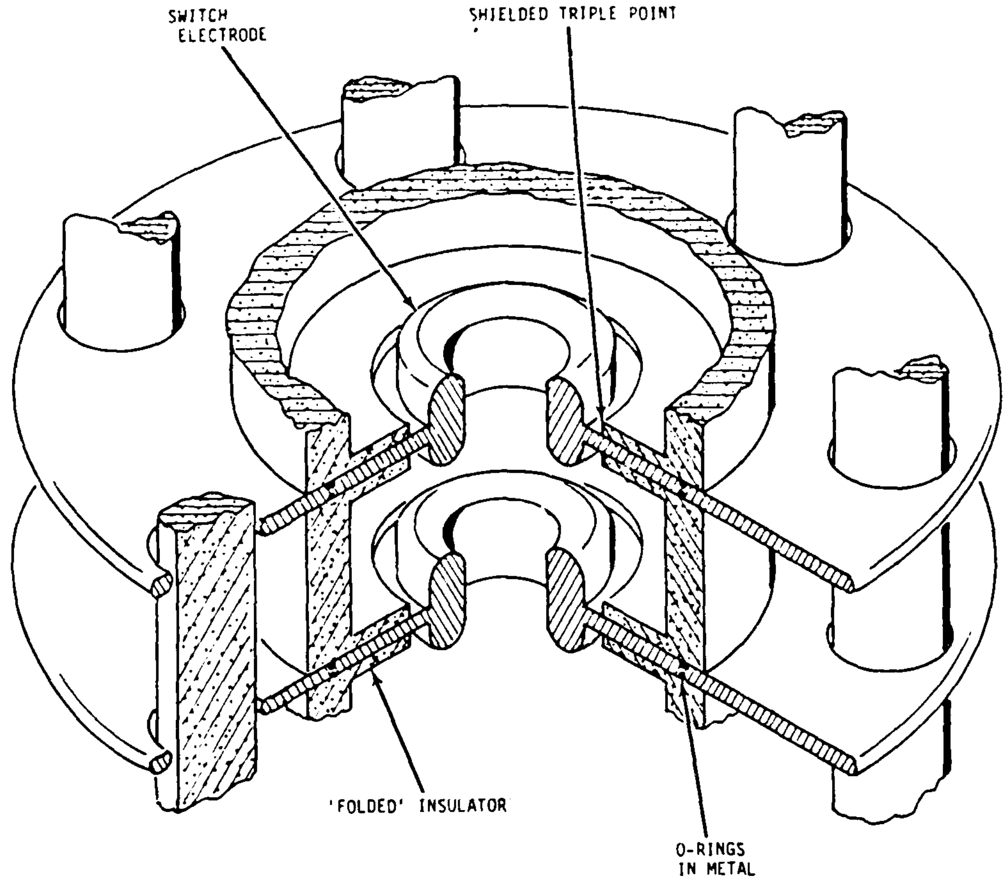


FIGURE 21

DQ SWITCH SECTION
WITH FOLDED INSULATOR

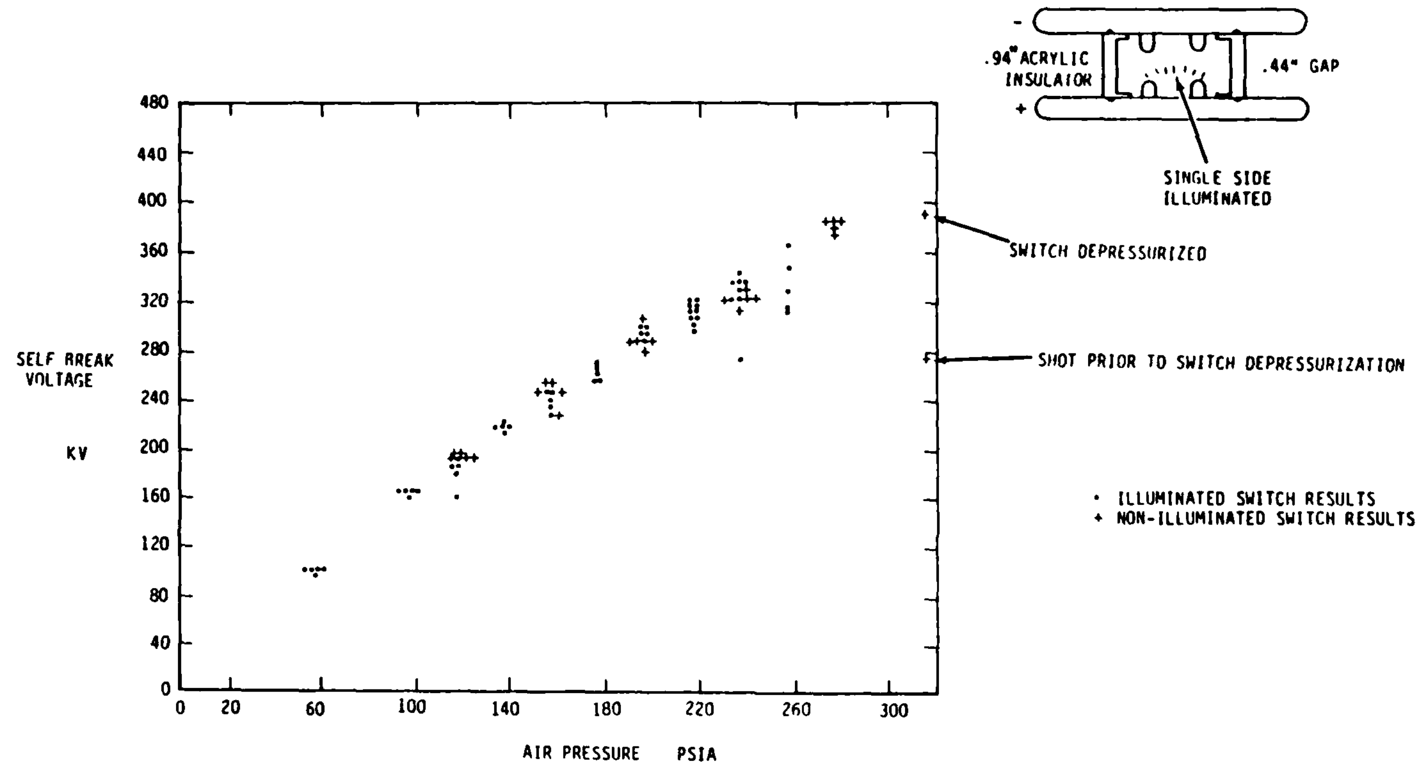
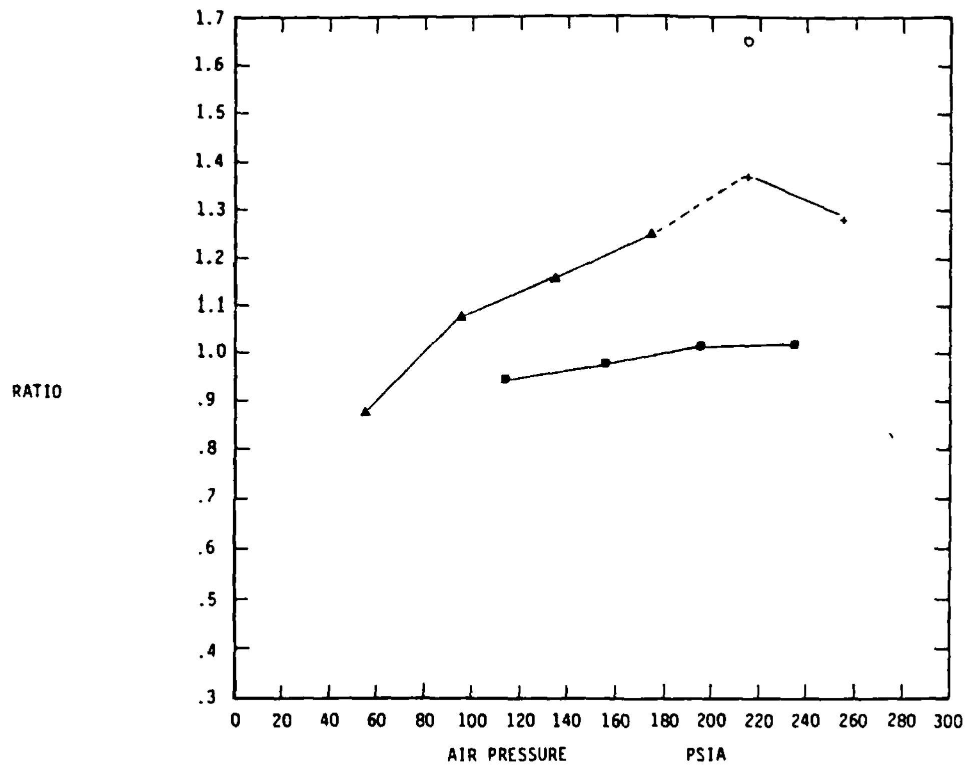


FIGURE 22 7/12/79 TESTS



.94" SPACER

.44" GAP

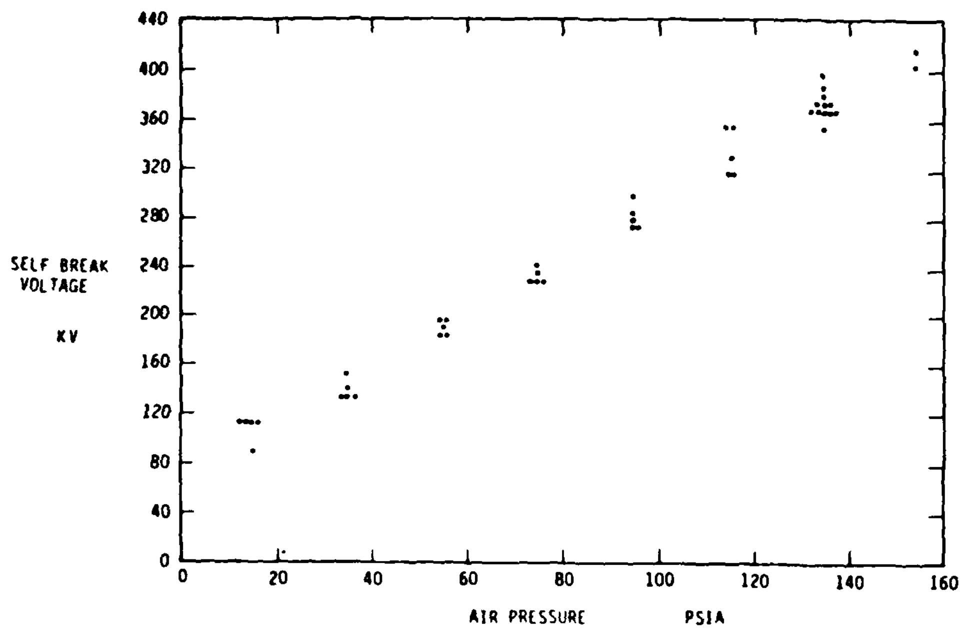
O-RINGS IN METAL

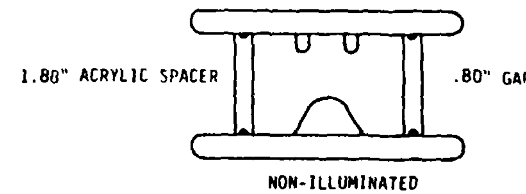
STRAIGHT-SIDED INSULATOR
- ○ 7/6/79 SINGLE SIDE ILLUM., SHARP GROOVES CUT AROUND INSULATOR BASE
- + 6/29/79 SINGLE SIDE ILLUMINATED
- ▲ 6/26/79 DOUBLE ILLUM.

FOLDED INSULATOR
- ■ 7/12/79 SINGLE SIDE ILLUMINATED

FIGURE 23 $\frac{\text{MEAN ILLUMINATED BREAKDOWN VOLTAGE}}{\text{MEAN NON-ILLUMINATED BREAKDOWN VOLTAGE}}$,COMPARISON BETWEEN INSULATOR TYPES inherently weak. In order to strengthen these points, a filet was made by radiusing the inside edges of several insulators. Unfortunately, this caused the switch self-break to scatter greatly, and wall tracks were observed on the inside of the insulators fabricated with the trial filet. The straight-walled, non-radiused design was kept.

One last interesting point is worth reporting. A 1978-type full-sized DQ switch insulator (O-rings in plastic, straight walls) was tried in the test stand and not illuminated. This was believed to be the approximate condition of dark switch sections at Casino. It could not be made to scatter appreciably or fail. It worked without a problem. Maximum voltage reached was 420 kV, corresponding to 4.2 MV at Casino. The self-breakdown curve is shown in Figure 24. So while these tests seemed to clearly demonstrate that the flange design gave superior wall track suppression, it is not clear why the modification was needed, if a large straight section could go to the equivalent of 4 MV. Nevertheless, because it demonstrated improved performance, the flanged insulator design was used at the subsequent Casino tests. Although several attempts have been made to return to straight-walled insulators since these tests, none have yet been successful for any number of shots.





NO WALL TRACKS SEEN ON INSULATOR.

FIGURE 24 7/30/79 TESTS

5.0 The 1979 Casino Tests

The DQ switch taken back to Casino in 1979 was the same as the 1978 model, except for two changes. First, the insulators had been modified from the straight-wall insulators to the folded type. Second, the trigger section was slightly modified in trigger plate design and insulator length. The trigger section used at Casino initially in 1979 is shown in Figure 25. Three sets of insulators were taken, made of acrylic, natural acetal and PVC.

Acrylic insulators were installed in the DQ switch and used for shots 379 through 388. Unfortunately, the stress rods had not been torqued sufficiently to prevent an accordian-type motion of the switch when it was fired. This motion broke the insulators. As a result of the stress rod stretching, a torque of 30 foot-pounds was used for each rod. This was considerably greater than the switch had been previously torqued, and prevented subsequent damage of this type.

Acetal insulators were installed next. Testing started at a very low pressure (5 psig air) on the DQ switch. It was observed that the trigger section had been assembled in error. It was observed that the self-break voltage scatter of the DQ switch was very narrow (see Figure 26), up to approximately two megavolts. Above that point, it scattered (shot 408, Table I). At this time, it was discovered that the switch needed conditioning. Four 4-MV shots were obtained as a result, beginning with shot 440. The series was interrupted when the PVC blowdown tank cracked, in a mechanical failure having nothing to do with the electrical operation of the switch. Figure 26 plots the data from Table II and compares the conditioned shots with the non-conditioned ones.

The switch conditioning phenomena will now be discussed. This is a clearly-defined effect, well-known in some other high current switches before these tests. Its cause is still unknown. The effect is observed when a switch is fired at very high current. On subsequent shots at high current, the switch will

DQ SWITCH TRIGGER SECTION

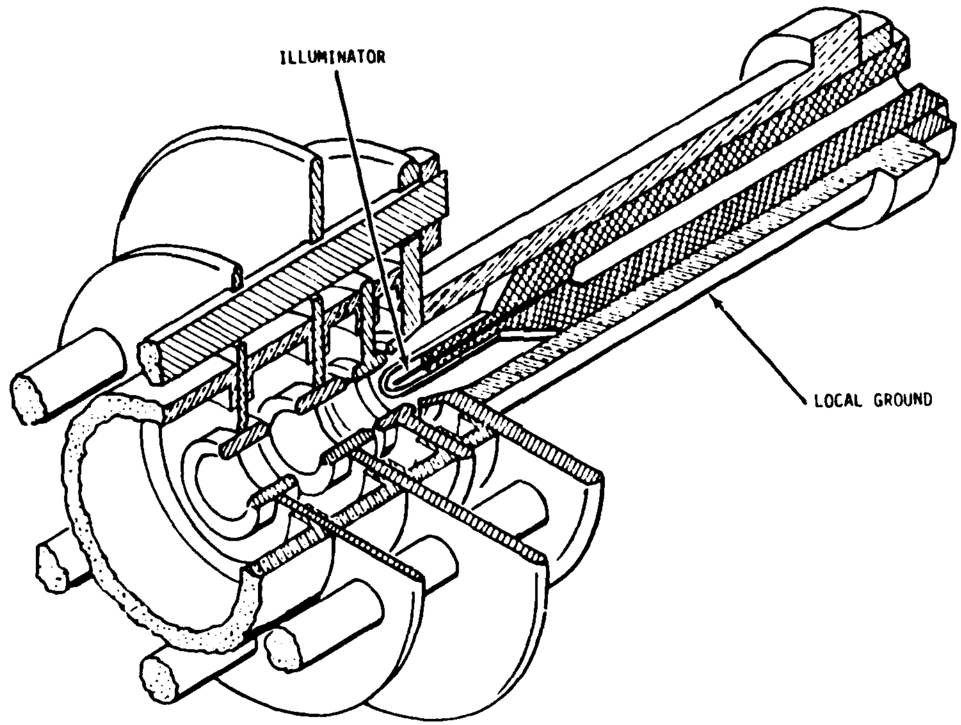


FIGURE 25 DQ SWITCH TRIGGER SECTION AUGUST 1979

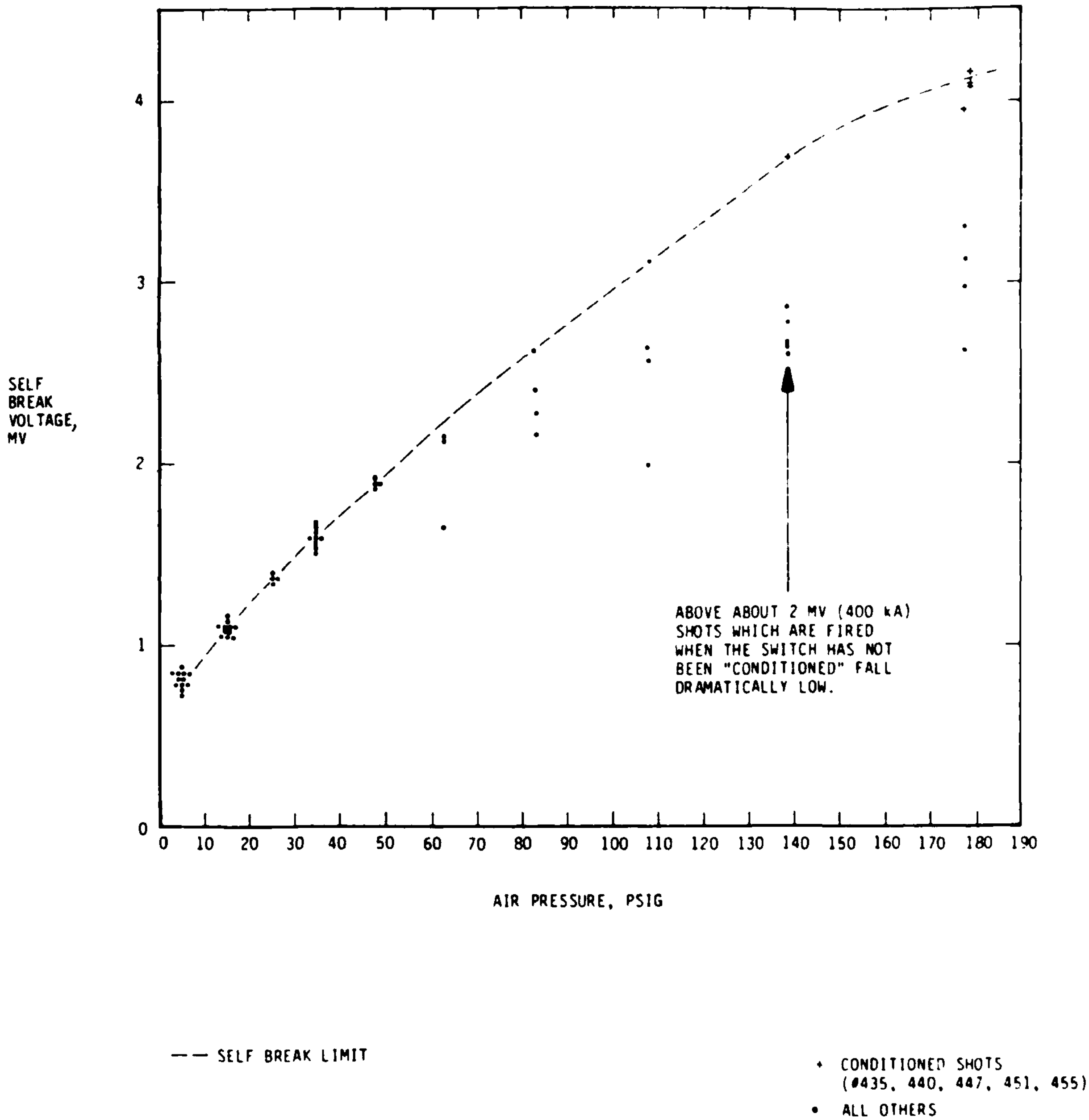


FIGURE 26 DATA FROM TABLE II (12" ELECTRODE PLATE REVERSED)

TABLE I

CASINO TESTS, ACETAL INSULATORS

SHOT #	DQ SWITCH PRESSURE, PSIG SF_6	BREAKDOWN VOLTAGE, MV	SHOT #	DQ SWITCH PRESSURE, PSIG SF_6	BREAKDOWN VOLTAGE, MV
389	5	.82	423	139	2.65
390	5	.87	424	178	2.98
391	5	.79	425	178	2.63
392	15	1.15	426	35	1.54
393	15	1.13	427	35	1.59
394	15	1.07	428	35	1.46
395	15	1.11	429	35	1.59
396	25	1.37	430	35	1.57
397	25	1.39	431	15	1.11
398	25	1.37	432	15	1.11
399	25	1.35	433	15	1.11
400	35	1.61	434	15	1.07
401	35	1.59	435	139	3.69
402	35	1.69	436	139	2.67
403	35	1.67	437	15	1.09
404	48	1.91	438	15	1.09
405	48	1.89	439	15	1.07
406	48	1.87	440	178	3.96
407	48	1.89	441	178	3.32
408	63	2.13	442	178	3.13

NOTES

1) 12" Electrode Plate reversed.
2) Pulseline rollover voltage is 4.0 MV unless indicated by * when it is 4.6 MV

SHOT #	DQ SWITCH PRESSURE, PSIG SF_6	BREAKDOWN VOLTAGE, MV	SHOT #	DQ SWITCH PRESSURE, PSIG SF_6	BREAKDOWN VOLTAGE, MV	NOTES
409	63	2.15	443	5 (SF_6)	1.80	(not included in Figure 25)
410	63	--	444	5	.83	
411	63	1.65	445	5	.85	
412	83	2.28	446	5	.83	
413	83	2.17	*447	180	4.08	
414	83	2.63	448	5	.80	
415	83	2.41	449	5	.85	
416	108	1.98	450	5	.82	
417	108	3.11	*451	180	4.09	
418	108	2.56	452	5	.85	
419	108	2.63	453	5	.82	
420	139	2.61	454	5	.85	
421	139	2.78	*455	180	4.15	(blowdown tank cracked)
422	139	2.87				

TABLE II

CASINO TESTS, ACETAL INSULATORS

SHOT #	TRIGGERED?	DQ SWITCH BREAKDOWN VOLTAGE, MV	7030 DELAY SETTING, nS	TIME DELAY BETWEEN TRIGGER PULSE ARRIVAL AND BREAKDOWN, nS (+10 nS)
456	Yes	1.83	600	80
457	Yes	1.85	550	130
458	Yes	1.93	650	50
459	Not Attempted	2.20	---	---
460	Not Attempted	2.20	---	---
461	Yes	1.96	650	60
462	Not Attempted	2.19	---	---
463	Yes	2.02	650	70

display a lowered self-break voltage. That is to say, it will "prefire". However, it has been repeatedly observed that if, after a high current shot, the switch is fired a few to a few thousand times at low current, then the switch "conditions", and it may then be fired at high current and will display quite accurately the expected self-break voltage. This phenomena has been observed with at least brass and several tungsten alloys in several different types of switches. It has been observed with water, oil and gas dielectrics. The traditional explanation for this effect is that it results from whiskers or protrusions being formed on the electrode surfaces by the high current shots. It is suggested that the low power conditioning shots then burn off the irregularities, and thereby condition the switch. The only trouble with this explanation is that no one has yet consistently found such irregularities, and workers are now looking for more subtle explanations possibly in the quantum structure of the electrode surface.[5]

Beginning with shot 437, in Table I, one can see a conditioning effect. Shots 437, 438 and 439 are low power shots which give a breakdown voltage reproducibility to within one percent, well inside the precision of the data network. Shot 440 was expected to break at four megavolts, and it was actually measured at 3.96 megavolts. Again, the 40 kV difference has no meaning. Shots 441 and 442 were attempts to fire again at four megavolts without conditioning, without success. However, when the switch was conditioned with low power shots, four megavolts was again easily reached with shots 447, 451 and 455. Note the very tight voltage grouping of these three shots, typical of a properly illuminated conditioned switch.

Looking to the future, we are not concerned by the possible practical limitations of the conditioning phenomena. In a practical system, the requirement to condition can be avoided altogether by using parallel columns to reduce the current per column. Alternatively, the load of a system could be shorted for the conditioning. Finally, there are some indications that there may be other ways to condition a switch.

After shot 455, the test series was interrupted by a cracked air ballast tank. When the DQ switch was disassembled, it was noticed that the large type insulator closest to the trigger section was almost eaten away by arcing and melting. This turned out to be the indirect result of the inadvertently reversed 12-inch electrode plate, causing a 1.07-inch electrode gap in that section rather than the normal 0.80 inch. This also caused the trigger section to short out very early in the pulse ramp, thereby preventing external triggering of the switch. A punctured insulator flange was also noted. Four insulators were replaced with new ones (acetal), and a steel scuba bottle replaced the previous PVC blowdown tank, which had cracked. The scuba tank was laid on the bottom of the center conductor in the pulseline, and was connected to the switch by a six-foot long, 1/2-inch diamater Nyloseal tube. The 12-inch electrode plate was properly oriented upon reassembly of the switch.

Some evidence of triggering was seen during the next shot sequence, consisting of numbers 456 through 461. Also, the self-break voltage was 14 percent higher at 40 psig (air) with the properly oriented electrode plate. At that point, unfortunately, plumbing again intervened, and the blowdown tank air line blew off. A specially made aluminum blowdown tank was then made by the Casino shop and screwed into the bank of the switch, and the tests continued. Shots 462 and 463 also implied that triggering was occurring. Shots 456 through 463 are detailed in Table II. The primary evidence for successful triggering was the constancy of the switch self-break voltages and the lowering of these breakdown voltages whenever the switch was triggered. A schematic of the triggering system is shown in Figure 27.

Between shots 464 and 473, the DQ switch was high-voltage-tested again. The switch rapidly deteriorated in performance, and failed on shot 473. Apparently, combustion of the acetal with the switch air had occurred inside the switch, causing the walls to thin until they broke under the shock.

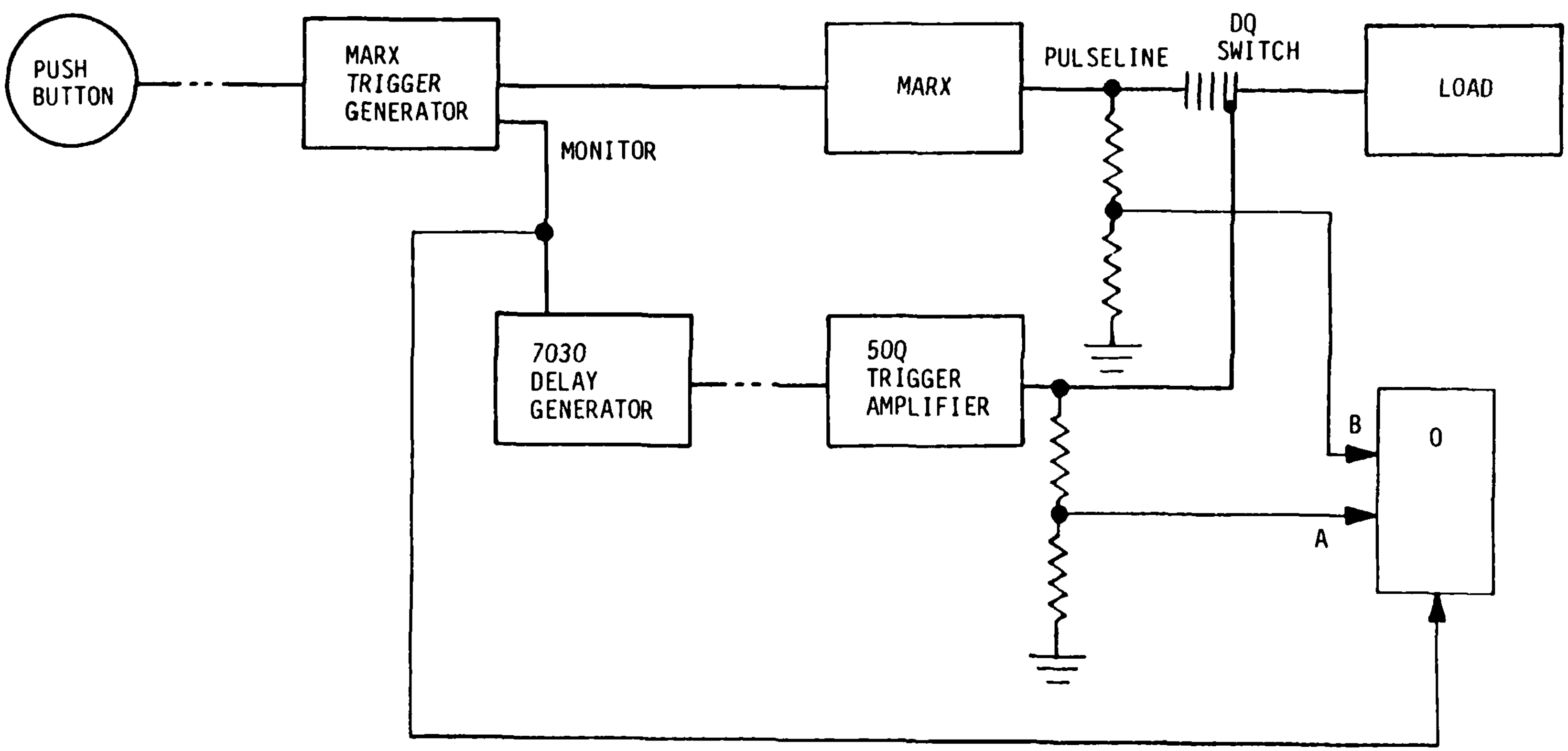


FIGURE 27 CASINO TRIGGERING SYSTEM

Next, the PVC insulators were installed. The switch was operated from shots 474 through 482 in the self-break mode, this time with SF_6, so that chemical reaction with the walls could not occur as readily. Unfortunately, the PVC would not stand up electrically to the high voltage shots, and it was abandoned.

A new set of acetal (Delrin) insulators was machined, along with a new five-inch trigger plate, and both were installed in the DQ switch. The new trigger section design is shown in Figure 28. SF_6 was used this time to prevent burning of the insulator walls, and to reduce the mechanical stresses on the switch. The switch operated from shots 500 through 551, when it depressurized. The shots were all in the self-break mode, with the emphasis on learning how many conditioning shots were required for four megavolt operation, and for what length of time the switch would stand up. It appeared as though two conditioning shots were required (at five psig SF_6) for reliable operation at four megavolts (50 to 55 psig SF_6). The switch lasted for 52 shots, including a total of 13 four-megavolt level shots, before it failed, due to a full power wall track inside one of the insulators. Another insulator had both flanges punctured with a minor connecting wall track. Apart from this, the insulators appeared in good shape. A plot of the high voltage shots versus time is shown in Figure 29.

In the next series of shots, acetal insulators were again used. SF_6 was used at the higher voltages and Argon at the lower voltages.

At five psig SF_6 (two megavolts), the DQ switch was triggerable, and had roughly 10 nS jitter with a breakdown delay of 120 nS and triggering range of about 15 percent. Becuase of the difficulties inherent in the delay measurement, it was difficult to achieve a greater resolution of jitter measurement than 10 nS. So there is some uncertainty as to this figure. Table III lists data from the four separate shot sequences run at five psig SF_6. The Marx jitter accounts for the large breakdown voltage scatter for a given breakdown delay. A 7030 delay setting of 530 nS appeared to be about the best operating point for the switch. At 600 nS, the 50Q pulse arrived too late for minimum jitter operation, while at 480 nS, it arrived too early.

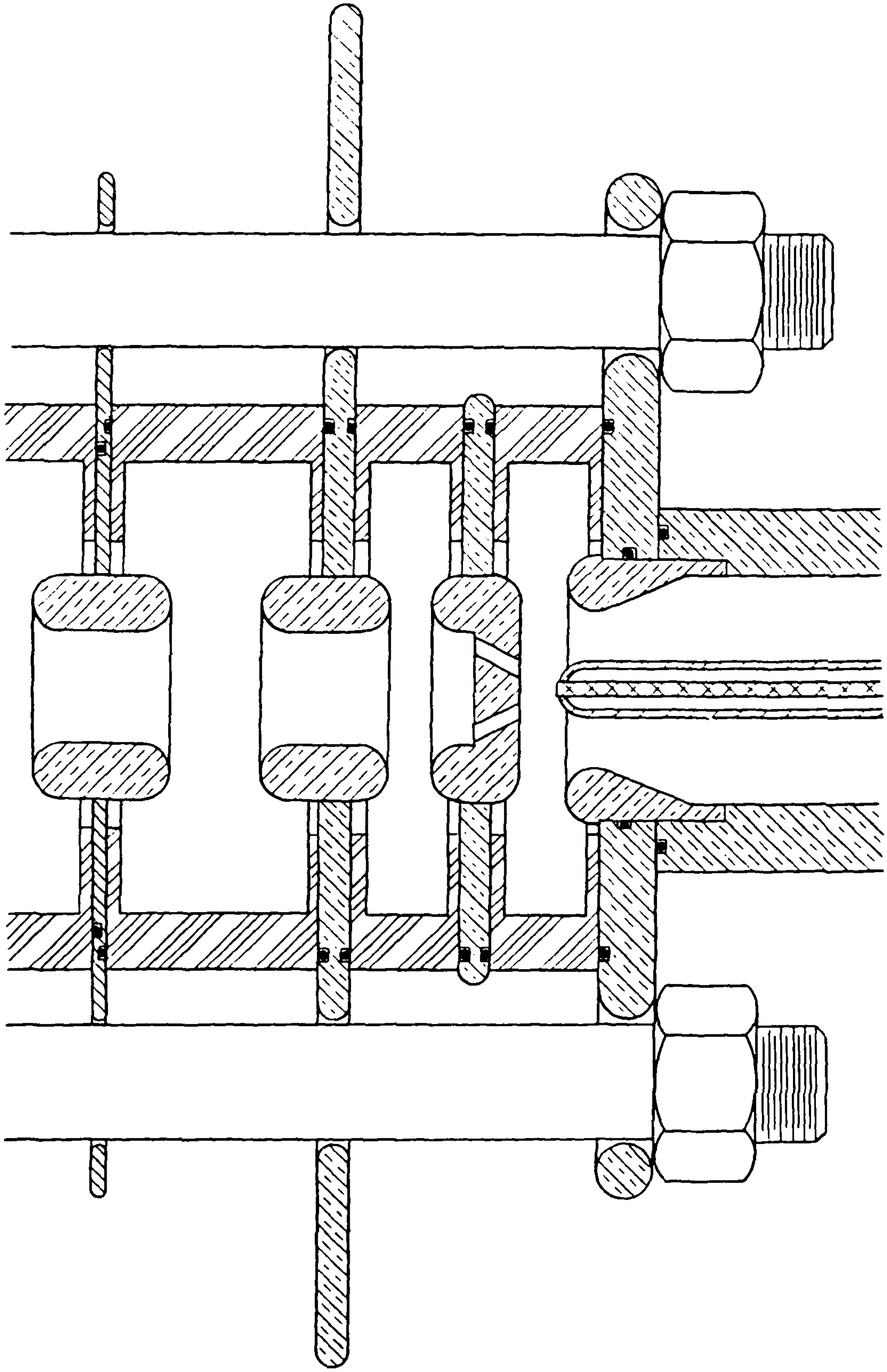


FIGURE 28 LATEST TRIGGER SECTION DESIGN

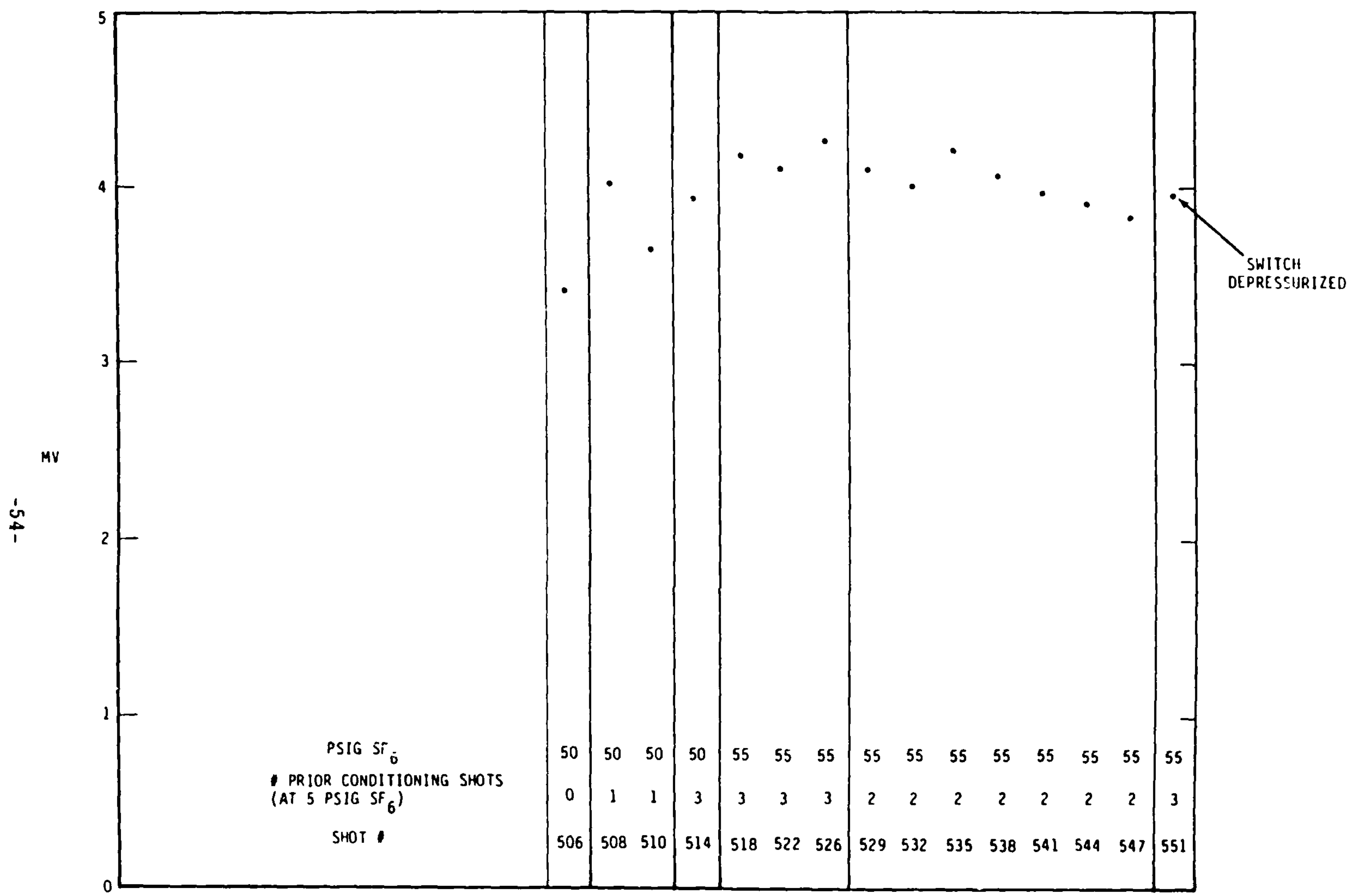


FIGURE 29 EFFECT OF CONDITIONING ON HIGH VOLTAGE SELF BREAK

TABLE III

CASINO TRIGGER TESTS

NOTES: 1) 5 psig SF_6
2) Acetal Insulators
3) "No" indicates triggering not attempted.

SHOT #	TRIGGERED?	TIME DELAY BETWEEN TRIGGER PULSE ARRIVAL AND BREAKDOWN, nS ($\pm$10 nS)	7030 SETTING, nS	DQ SWITCH BREAKDOWN VOLTAGE, MV
10/10/79				
552	Yes	70	600	1.85
553	No	---	600	2.12
554	Yes	80	600	1.81
555	No	---	600	1.89
10/11/79				
556	Yes	70	600	1.85
557	No	---	600	2.02
558	Yes	90	600	1.78
559	Yes	60	600	1.93
560	Yes	No Data	600	1.89
561	Yes	50	600	1.85
562	No	---	600	1.93
563	No	---	600	No Data
564	No	---	600	1.97
565	No	---	600	1.89

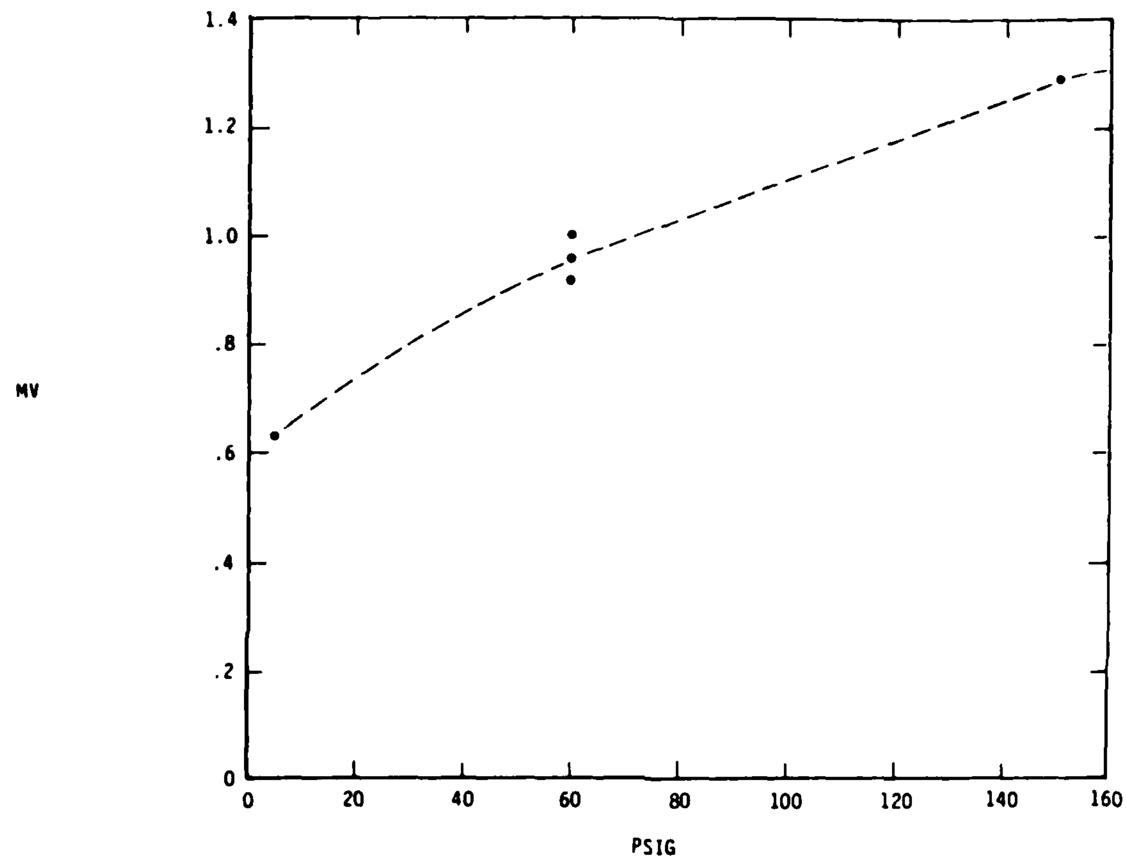
SHOT #	TRIGGERED?	TIME DELAY BETWEEN TRIGGER PULSE ARRIVAL AND BREAKDOWN, nS (+10 nS)	7030 SETTING, nS	DQ SWITCH BREAKDOWN VOLTAGE, MV
564	No	---	600	1.97
565	No	---	600	1.89
566	Yes	110	530	1.74
567	Yes	120	530	1.70
568	Yes	110	530	1.67
569	Yes	110	530	1.70
570	Yes	190	480	1.74
10/12/79				
571	Yes	142	480	1.78
572	Yes	125	480	1.63
582-584	DATA LOST			
10/16/79				
591	Yes	No Data	530	1.88
592	Yes	No Data	530	1.78
593	Yes	No Data	530	1.78
594	Yes	120	530	1.72
595	No	---	530	1.91
596	Yes	115	530	1.68
597	No	---	530	2.11

When attempts were made to trigger the DQ switch at three magavolts and 2.5 megavolts, there was no apparent success. Subsequent investigation indicated that the illuminating circuit was inadvertently shorted out by an arc at these higher voltages. The trigger section has since been modified to correct this problem. In reality, it should be easier, not harder, to trigger the switch at higher voltages.

During these tests, a quick self-break curve for argon was run. The curve is shown in Figure 30. Triggered shots were then run, using argon at about 0.8 megavolt (60 psig Ar). The results, which are substantially the same as those achieved in SF_6 at two megavolts, are shown in Table IV. Again, the triggering range was 10 to 20 percent, with approximately 10 nS jitter (200 to 230 nS on 7030). These successful trigger tests indicated that the series column of the DQ switch could be triggered.

The command jitter of 10 nS is considered too high in our opinion. It is thought to be caused by inadequate illumination current. One simple attempt was made to correct this in one of the last test series of 1979. A piece of conductive rubber tubing (Tecknit) was connected to the trigger pin in such a way that it came in contact with the grounded outer conductor. The resistance of the Tecknit was several hundred ohms, so the illumination current was on the order of one kiloampere. The switch gave the appearance of triggering for two shots at three megavolts (27 psig SF_6), but then apparently the Tecknit failed. When the switch was removed, it was discovered that the Tecknit had fragmented and no longer could serve its function. In future tests, the Tecknit will be replaced by a coiled wire which will not be sensitive to heat.

This set of DQ switch insulators used during the trigger tests lasted a total of 68 shots, including 15 at the three-megavolt level. Later inspection showed that there were no wall tracks or punctures anywhere on the insulators



SHOT NUMBERS

603-605
608
612

FIGURE 30

DQ SWITCH SELF BREAK CURVE FOR ARGON

TABLE IV

CASINO TRIGGER TESTS

NOTES: 1) 60 psig Argon
2) Acetal Insulators
3) #605 was at 150 psig.
4) "No" indicates triggering not attempted.

SHOT #	TRIGGERED?	TIME DELAY BETWEEN TRIGGER PULSE ARRIVAL AND BREAKDOWN, nS (±10 nS)	7030 SETTING, nS	DQ SWITCH BREAKDOWN VOLTAGE, MV
604	No	---	---	.92
606	Yes	50	330	.90
607	Yes	125	230	.78
608	No	---	---	1.00
609	Yes	135	230	.81
610	Yes	130	200	.79
611	Yes	180	170	.78
612	No	---	---	.97
613	Yes	70	280	.81

except for the trigger sections, where a considerable amount of burned Tecknit had ended up, shorting them out. All in all, this is more than an adequate performance. Extensive life testing is time consuming on a large facility, and for the DQ switch, will have to wait for the next phase of testing.

6.0 Conclusion and Next Steps

The basic conclusion of the 1979 tests is that the feasibility of the DQ switch technology has been demonstrated. However, some engineering improvements are clearly required. It should be emphasized that even at the end of the preceding year's tests, the DQ switch, in some respects, demonstrated performance superior to that of existing water switches at the same level. One of these, of course, was reproducibility of operation.

Based on the experience in the most recent test series, a fairly clear picture has begun to emerge of the way in which the flanged insulators work, and the method by which they provide improved performance. As is mentioned above, they first of all move the triple point of the insulator to a relatively low electric field region. This appears to slow down the launching of the streamer in the first place. Secondly, once started, the streamer has to move across the electric field for some distance before it can turn and meet a parallel accelerating field down the outside wall of the insulator, parallel to the axis of the switch. However, the recent Casino tests have indicated that at the highest stresses, four megavolts on the switch, 400 kilovolts per section (80 kV/cm^3 on the insulator), the rising electric field on the switch at some time (before or during gap breakdown) discharges the vertical wall of the insulator. There is no immediate feeding this discharge from the electrodes because of the insulating flanges. With the vertical insulator wall discharged, the applied electric field, on the order of 400 kilovolts, is now dropped across the two end flanges, one at each electrode. Insulation is then provided by the bulk dielectric strength of the flanges at the ends of the switch. This explanation is suggested by the fact that when flanged insulators did fail in normal use, either because of inherent imperfections, or perhaps because of some lifetime effect, they were observed to punch through in small tracks through the end flanges, but immediately tangent to the inside wall of the insulators.

In the most recent tests at Casino, the thickness of each end flange was approximately one-half of a centimeter. With the two flanges, the bulk dielectric stress on the plastic after the discharge of the walls, then became approximately 400 kilovolts per centimeter. This figure exceeds the DC bulk dielectric strength of the acetal by approximately a factor of two, and may be approaching the safe operating limit for repeated pulses. Thicker flanges and materials with higher dielectric strength will be tried in the future. Besides acetal, which has proven adequate, we are now looking at several other materials, including other plastics and special glasses. Two considerations are important in this search. First is bulk dielectric strength, but just as important are considerations of practical engineering of the insulators, including methods of shaping and costs. The pulsed bulk dielectric strengths of commercial grades of plastics and glass suitable for this work are now under test. How far we can carry the dielectric strength of the switch insulators is now a direct matter of available dielectric strengths and suitable manufacturing techniques.

The triggering of the DQ switch has always been one of its most interesting features. Some people have felt that because it consists of series switches in a column, triggering might present an especially difficult problem or prove to be insurmountable altogether. The switch is fired from the positive end, with the trigger section closing first, followed by each section closing in turn. While computer and analog modeling have both indicated that this would be the case, it was not until the most recent test series that it was demonstrated that triggering was possible. In this test series, the DQ switch was triggered up to a little above two megavolts. The observed jitter was less than 10 nanoseconds, but perhaps not a great deal less. This fact demonstrates that triggering of the column is inherently possible.

When attempts were made to trigger at higher voltages, such as 2.5 or 4 megavolts, it was found that while the switch worked perfectly well in the self-breaking mode in these regimes, it would not trigger. This has been traced to a difficulty with the trigger section in itself. Apparently the trigger section broke down early and shorted out on those shots where the voltage was allowed to rise above two megavolts. In breaking down early, the trigger section was shorted out when the voltage across the switch was still too low to fire the switch. However, enough time remained for the voltage along the switch to redistribute itself on the remaining nine sections. When the command trigger section did finally arrive at the switch, it found the trigger section shorted out and conducting. This shorted the trigger pulse to ground. This problem has been addressed by making several small mechanical changes in the trigger section itself which permit a field adjustment of the trigger electrode spacing.

The second area of interest in the DQ switch is the trigger jitter. Command jitter should be as low as possible, on the order of one or two nanoseconds, to provide good current sharing between adjacent columns in multi-column arrays and good synchronization between adjacent modules. The jitter which has been observed to date, on the order of 10 nanoseconds or less, is far superior to any water switch performance. But, it is our belief this figure can be substantially reduced. In the most recent tests, the illumination current, which has a direct bearing on the jitter of the trigger section, was capacitively coupled in the return path to ground. This has been changed in the newest version of the switch so that a small inductive wire will allow more and a longer-lasting current pulse to be provided to the illumination electrodes.

Neither of these last two modifications to the trigger section of the DQ switch have been checked out on the full DQ switch sections at Casino, as of the writing of this report. It is intended that they will be tested in the next test sequence early in 1980. Now that the feasibility of the switch has been demonstrated, there are several other important areas which will be investigated in the next test periods in 1980. These can be identified broadly as follows:

1. The performance of engineering life tests on a single column at the four megavolt, 800 kiloampere level, in order to determine effective

lifetime, and to develop ways of extending that lifetime by more subtle modifications to operating parameters and mechanical design.

2. The testing of a three-column array; that is, a switch which consists of not one, but three parallel DQ columns, and the measurement of its performance. To be searched for here particularly, of course, are not only the low jitter of commanding three columns in parallel, but the lower effective inductance that this array would provide for low inductance, low impedance systems. These tests would first be conducted, again, at Casino at the four megavolt level. Current in each of the switch columns, of course, would be dropped by two-thirds from 800 kiloamperes to approximately 270 kiloamperes. It is expected that this lower current per column may also preclude entirely the need for conditioning of the switch array between firings.

3. Extending the switch technology to a still higher power regime, using a machine such as the DNA AMP machine, located at the HDL facilities. The switch array to be tested on this machine would be a three- to six-column array, operated at peak holdoff voltages of from two- to four-million volts with peak currents ranging from one- to three-million amperes. Successful operation at these powers with the resulting practical engineering details would result in a switch which could then be used to replace the highest power water switches now in use in the United States.

The DQ switch has already arrived at a point where it has demonstrated features which are superior to many water switches in use today. It has a lower resistive loss; it is triggerable with lower jitter, and operates with more shot-to-shot reproducibility than corresponding water switches. Having passed from the feasibility demonstration phase, and now entering into engineering development, the switch will quickly reach a point where it can be used wherever multi-module machines, precision triggering or especially low inductance with good reproducibility is required. First rate system performance will require top performance from the switches.

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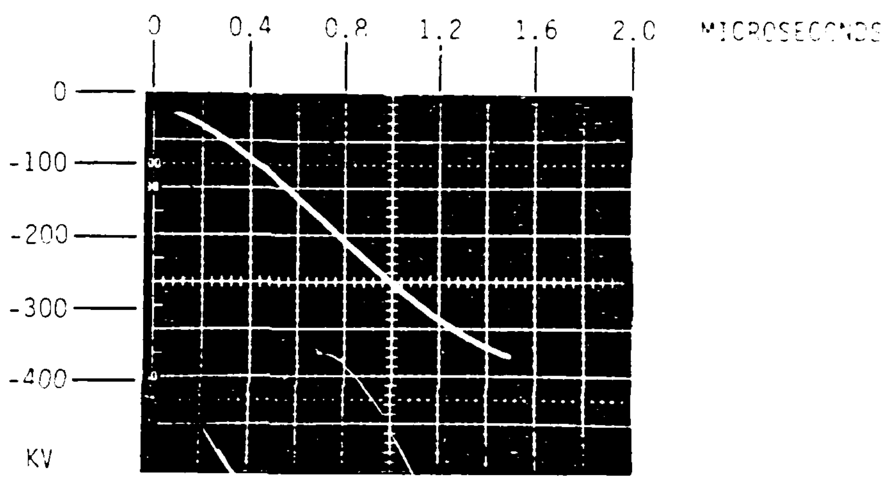
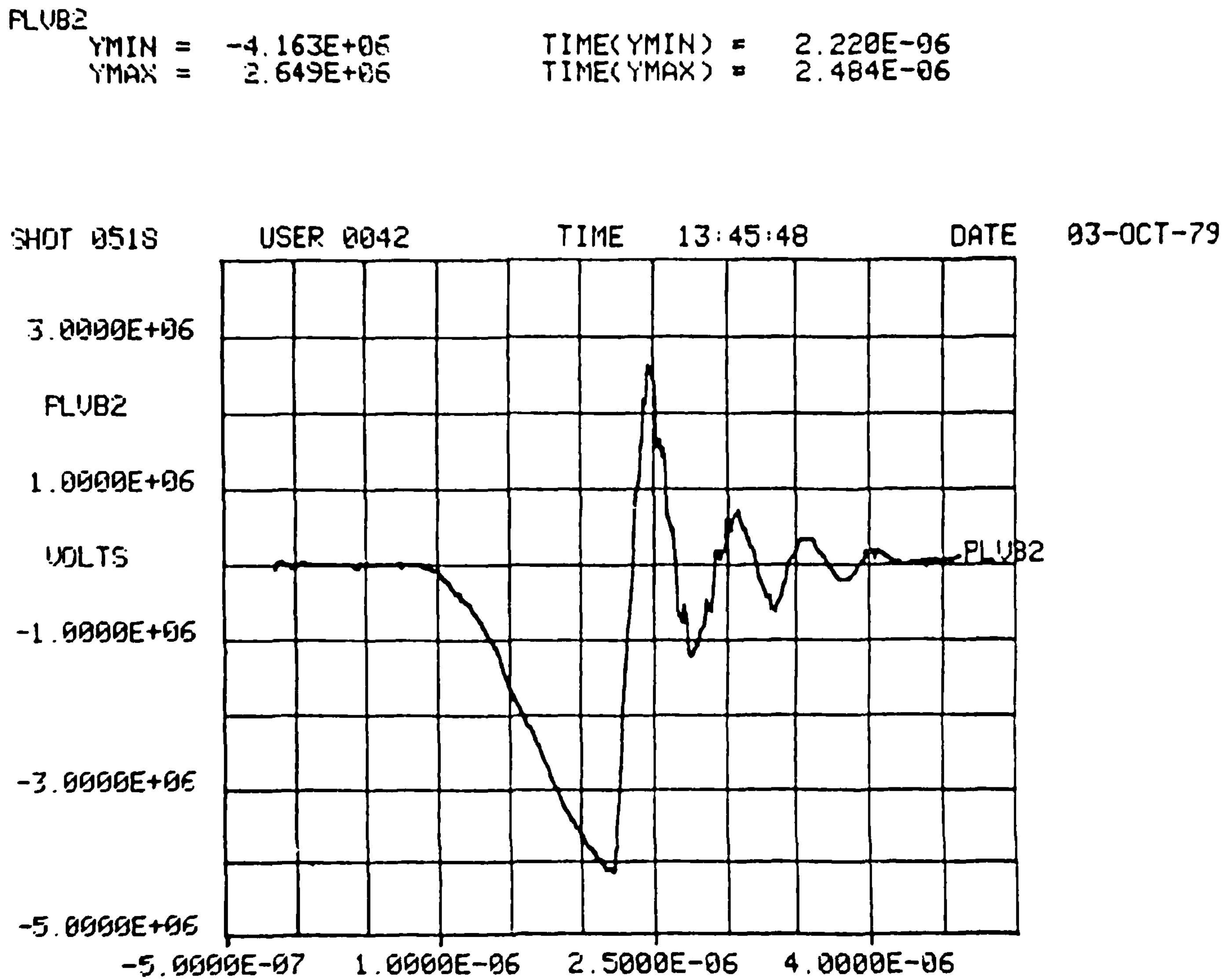


APPENDIX I

TYPICAL SINGLE SECTION SWITCH TEST WAVEFORM



APPENDIX II

TYPICAL CASINO PULSELINE VOLTAGE WAVEFORM WITH DQ SWITCH FIRING AT 4.16 MV.

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