DEVELOPMENT OF AN 18-MEGAVOLT MARX GENERATOR *

K. R. Prestwich and D. L. Johnson
Sandia Laboratories
Albuquerque, New Mexico

Summary

An 18-megavolt, 1 megajoule Marx generator has been constructed and tested to 11 MV as the primary energy store of the Hermes II flash x-ray machine.[1] A geometrical arrangement for the capacitors that takes advantage of the stray capacities to provide a wide triggering range and fast Marx erection time was developed from model and circuit studies. The design parameters of the Marx were checked by constructing and testing a 4 MV, 100 kJ generator using components proposed for the 18 MV system. Spark gaps were developed specifically for the generator and have operated successfully for over 50,000 gap firings.

Introduction

Marx generators have been used to generate voltages up to 2 MV for impulse testing of dielectric breakdown for many years.[2] The peak voltages and energy storage of Marx generators have been significantly increased by the development of multimegavolt flash x-ray machines.[1,3,4,5] The Hermes II Marx generator is presently the highest voltage, largest energy storage unit operating in a flash x-ray machine.

Model and Circuit Studies

Voltage multiplication is accomplished in Marx generators by charging capacitors in parallel and discharging them in series. Spark gaps are generally used to switch from parallel to series arrangement. Usually one or two of the gaps are triggered and the remainder are overvolted by the transient voltages within the generator. Proper stage-to-stage capacitive or resistive coupling must be maintained to insure that the untriggered spark gaps will be overvolted.[2,6] The simple Marx circuit shown in Figure 1 can be used to explain capacitive and resistive coupling.

The capacitors can be arranged such that the stray capacity (C_R) between every other stage is large. These stages are connected with charging resistors. If gaps (1) and (2) in Figure 1 are triggered, point A becomes clamped at 3 V_o. If this is a long generator and the capacity to ground from every capacitor is small compared to C_R, the voltage across gap (3) becomes approximately $\frac{2 V_o C_R}{C_R + C_g}$. The voltage across C_R decays to zero with a time constant of $R(C_R + C_g)$ and the voltage across gap (3) then approaches $2 V_o$. Since the voltage across each gap approaches twice its dc value, the Marx generator is called an n=2 generator. An n=2 generator can be triggered down to nearly 50 percent of the self-breakdown voltage (V_B) of the spark gaps. Similarly, if the coupling is such that the voltage across the spark gaps approaches pV_o, the generator is called an n=p generator and it would trigger down to 100/p percent of V_B.

To gain a more thorough knowledge of the operation of Marx generators, several model Marx generators were built. A capacitor arrangement was sought that would trigger over a large voltage range for any given spark gap setting, that would switch very rapidly, that could be easily assembled and maintained when constructed with 1/2μF, 100 kV capacitors, and that would have a reasonably low inductance. The Marx models were constructed with 10 kV, 1/4 μF capacitors. The effects of varying the value of charging resistors and stray capacities were investigated.

Figures 2 and 3 are schematic diagrams of two generators studied. The diagrams indicate the mechanical arrangement of the capacitors and resistors. By charging half of the capacitors to plus V_o and half to minus V_o, the required number of spark gaps is halved.

The type S Marx generator has capacitive coupling that varies from n=1 to n=5 across the generator. The resistive coupling is n=6 after the first six gaps have fired but varies from n=2 to n=5 if one to five gaps have fired. If three gaps were triggered, the minimum trigger voltage was 50 percent of V_B. If five gaps were triggered, the minimum trigger voltage was 26 percent of V_B. The minimum firing voltage was not affected by locating the triggered gaps at different points in the generator if three or five adjacent gaps were triggered. This layout has the lowest inductance of any of those considered.

The type Z generator has n=3 resistive and capacitive coupling. If three gaps were triggered, it would fire down to 30 percent of V_B. Triggering five gaps did not increase the firing range. If the resistors were connected in n=6 configuration and five gaps triggered, the generator would run at 20 percent of V_B. The inductance of this generator was measured to be 69 μH.

Figure 4 is a plot of switching time versus the fraction $2 V_o/V_B$ for both the S and Z Marx generators where $2 V_o$ is the dc voltage applied across each spark gap.

Streak photographs of the Z Marx were taken to show the firing time sequence of the spark gaps. Figure 5 is a plot of relative breakdown times of each gap taken from one of the streak photographs. The gaps are numbered sequentially from the ground end with gaps 1, 2, and 3 the triggered gaps. The interesting point is that, after 23 gaps had broken down, the gaps from the high voltage end began to fire sequentially, and finally the last seven gaps broke down simultaneously.

*This work sponsored by U.S. AEC.

4 MV-Marx

To further model the operation of this type of Marx generator, a 4 MV, 100 kJ type Z generator was constructed using the capacitors, spark gaps, resistors, and support structure proposed for the 18 MV generator. Since this Marx generator is the energy storage system for a flash x-ray machine called Hermes I,[1] the load of the Hermes II Marx generator was also modeled.

Figure 6 is a drawing of one row of the Hermes I generator. The generator consists of six complete rows and one partial row to provide electrical grading on the high voltage end. There is a six inch separation between rows of the eight inch diameter capacitors. Figure 7 is a photograph of the complete Marx generator before installation in its steel tank (10 ft wide by 12 ft long by 12 ft high) and immersion in transformer oil. The charge resistors are copper sulfate resistors constructed with vinyl tubing housings and copper tubing terminals. The charge resistors and ground resistors are 1.2 kΩ and 25 kΩ between each row, respectively. These resistors, along with the series resistance inherent in the Marx, discharge the generator with a 16 μs time constant. The spark gaps are individually housed, since analysis indicated that ultraviolet coupling between gaps was not necessary in this type of generator.

The generator has 22 μH inductance, 13.1 nF series capacitance, and 4Ω series resistance. C_g (see Figure 3) is estimated to be 45 pF, C_R is approximately 90 pF, and the strays from each stage to ground are less than 20 pF. The first approximation indicates capacitive division would immediately increase the gap voltage to 4 V_o and resistive coupling would increase it to 6 V_o with a time constant of about 0.15 μs. The Marx generator is usually operated with V_o equal to $V_B/3$. Therefore, the gap is immediately overvolted by 20 percent of its breakdown voltage. The gap voltage increases towards 80 percent overvoltage until breakdown occurs. The generator will operate down to 41 percent of V_B.

18-MV Marx Generator

The 18-MV generator developed for Hermes II is similar to the Hermes I generator except that each stage consists of two 1/2 μF - 100 kV capacitors in parallel. The cantilever supports (see Figure 6) were modified to increase the arc tracking length. There are 186 capacitor stages and 93 spark gaps in 31 rows. The generator is immersed in transformer oil in a steel tank 20 ft inside diameter and about 40 ft long. The shortest distance from the Marx generator to the tank wall is 4 ft.

When the capacitors are charged to 103 kV, the generator stores one MJ of energy. Its series capacity is 5.38 nF, and it charges a 5.6 nF transmission line. The calculated inductance and series resistance is 80 μH and 20 Ω. The charge resistors are 1.5 kΩ per section and will discharge the generator with a time constant of 25 μs. The transmission line is charged in 1.5 μs. With these parameters the Marx generator could charge the transmission line to 16.3 MV. At the present time the capacitors have been charged to 73 kV (1/2 MJ energy storage). The Marx generator was grounded through an inductor when the output voltage reached 11 MV.

In this generator C_g (see Figure 3) is estimated to be 45 pF, C_R is 190 pF, and the capacity per stage to ground is less than 10 pF. Therefore, capacity coupling would increase the voltage across the spark gap to 4.9 V_o immediately. It would further increase to 6 V_o with a time constant of 0.3 μs. The generator has been fired down to 40 percent of V_B.

One possible equivalent circuit for the Hermes II x-ray generator is shown in Figure 8. The 2000 pF capacitor representing the inner Blumlein transmission line must be isolated from ground by an inductor, since it becomes the high voltage terminal during discharge of the transmission line. The voltage appearing across the isolating inductor during charging of the transmission line also appears across the x-ray tube. This voltage, called the prepulse voltage, is detrimental to the operation of the x-ray tube. Hermes II voltage traces are shown in Figure 9, the oscillating voltage preceding the main pulse is the prepulse voltage. The circuit shown in Figure 8 was analyzed using an analog computer. This study showed that increasing the voltage across the strays from the high voltage end of the Marx to ground would increase the prepulse voltage from 3 to 18 percent of the Marx output voltage. One way that the voltage across the strays could be varied in the x-ray machine was to change the location of the trigger gaps. Experiments on the machine showed that much lower amplitude prepulses were present if the triggers were located eight rows back from the high voltage end of the generator. Figure 10 shows voltage traces with a small prepulse voltage.

Spark Gaps

A pressurized, individually housed spark gap is used to switch the Hermes' Marx generators. The gap, shown in Figure 11, has a self-breakdown voltage characteristic as shown in Figure 12.

Tests to determine a suitable electrode material were performed by discharging an L-C circuit of 2.4 μH and 1.25 μF charged to 180 kV through the spark gap. Peak currents of 130 kA were produced in a sinusoidal waveform of period 10 μs and decay time constant of 45 μs. Using a dry nitrogen fill gas at a constant pressure, the capacitors were charged and then discharged by the self-breakdown of the gap. This process was repeated until the voltage holdoff was reduced to 60 percent of its original value. Brass, chrome, and stainless steel were good for only three discharges, and molybdenum electrodes were good for seven discharges. A tungsten-copper-nickel alloy, commonly called heavy metal (89%W,7%Cu,4%Ni) was tested for 59 discharges. The breakdown voltage decreased to 74 percent of its original value for a gas pressure of 60 psi. The gas pressure was changed to 100 psi for the same number of discharges and the breakdown voltage changed to 63 percent of its original value. This test simulated the peak current of an early Marx generator design but, on a subsequent modification, it was more severe than necessary. It was felt that a better test would be to match, for the test circuit and Marx generator, the sum of the product of the current times the charge transferred in each half cycle until the current is 1/e of its original value.[6]

Using an electrolytic tank plotter, the shapes of the electrode, electrode holder, and spark gap holder were determined such that the electric field was constant over a 1.5 inch diameter circle in the center of the electrode and would fall off gradually at the edges. Nylon was chosen as a housing material because of its strength, machinability, and resistance to surface arcing (tracking).

Table 1
Hermes I Spark Gap Breakdown Voltage
After 1050 Firings

Gap #	40 psi			60 psi		
	$\bar{V}$ (kV)	% Decrease°	σ	$\bar{V}$ (kV)	% Decrease°	σ
1	147	10.3	3.5	191	18	8.4
2	136	17	5.9	176	24.4	5.9
3	138	15.8	5.4	178	23.6	4.4
4	135	17.7	4.1	170	27	6.2
5	147	10.3	4.6	192	17.6	7.9
6	142	13.4	4.6	186	20	3.7
7	154	6.1	1.3	210	9.9	2.2
8	134	18.3	3.8	166	28.7	2.2
9	145	11.6	2.8	198	15	1.4
10	131	20	3.0	174	25.3	4.7
11	149	9.1	2.5	196	15.9	4.8
12*	164		2.1	233		1.9

*12 is a typical new gap — σ will vary some from gap to gap when the gaps are new.

°Percent Decrease = $\dfrac{\bar{V}_{new} - \bar{V}}{\bar{V}_{new}}(100)$.

Table 2

Spark Gap Voltage	Percent of Firings	Max. First Cycle Current, kA	Max. Ringing Current, kA
< 60 kV	19	10.4	18.4
61-80 kV	37	13.9	24.6
81-100 kV	20	17.3	30.7
101-120 kV	11	21	37
121-140 kV	6	24	43
141-160 kV	4	28	49
161-180 kV	2	31	55
> 180 kV	1	35	61

The fill gas was changed from dry nitrogen to dry air to decrease the variance in breakdown voltages.

After 1050 firings of Hermes I, eleven of the spark gaps were removed and tested for breakdown voltage on a low-current power supply. The results of these tests are tabulated in Table 1 and shown in Figure 12. Table 2 gives the percentage of the 1050 firings for several ranges of spark gap voltage. The approximate peak currents are also given in this table.

Some of the electrodes were damaged uniformly over the constant stressed electrode area, while others were damaged only at one small spot. The degradation of the breakdown voltage for the small spot gaps was considerably worse than for the other gaps. Gap #2, 3, 4, 8, and 10 in Table 1 were small spot gaps, and #7, 9, and 11 were uniform breakdowns.

Hermes II spark gaps are identical to those used in Hermes I. Several gaps in Hermes II have tracked internally. The tracks were probably caused by contamination of these gaps with foreign particles resulting from changing the air line connections. Three gaps in Hermes I and one in Hermes II have tracked on the outside of the gap from the trigger terminal to the positive electrode causing mechanical failure of the gap. This problem was easily corrected by modifying the trigger terminal.

Conclusion

Based on information gained in developing and operating these generators, it is probable that even higher voltage Marx generators could be constructed with little difficulty. The inductance per stage of the Marx could be reduced by using lower inductance capacitors and arranging them in some combination of S and Z Marx generators. Since the spark gaps could operate with a substantial increase in current, Marx generators with higher energy storage could also be constructed by increasing the capacity per stage.

Acknowledgements

The authors would like to acknowledge the work of T. H. Martin in the Marx generator research, D. A. Butel in the mechanical design of the Marx generators, and thank R. S. Clark for performing many of the experiments.

References

1. T. H. Martin, "Design and Performance of the Sandia Laboratories Hermes II Flash X-ray Machine," Paper B-10 of this Conference.
2. J. D. Craggs and J. M. Meek, High Voltage Laboratory Technique (Butterworths Scientific Publications) London, Chapter 4, 1954.
3. W. T. Link and D. H. Sloan, "10^{12}-Watt Electron Beam," Record of IEEE 9th Symposium on Electron, Ion, and Laser Beam Technology, 77, May 1967.

4. W. P. Dejhe, J. P. Barbour, F. J. Grundhauser, and F. M. Charbonnier, "An Electron Accelerator with a Peak Bea Power of 10^{10} Watts," Proceedings of the 8th Annual Electron and Laser Beam Symposium, 505, April 1966.

5. B. H. Bernstein, Pulsed X-ray Prompt Gamma Simulator, Technical Report #BSD-TR-66-386, November 1966.

6. J. C. Martin, AWRE, Private Communication.

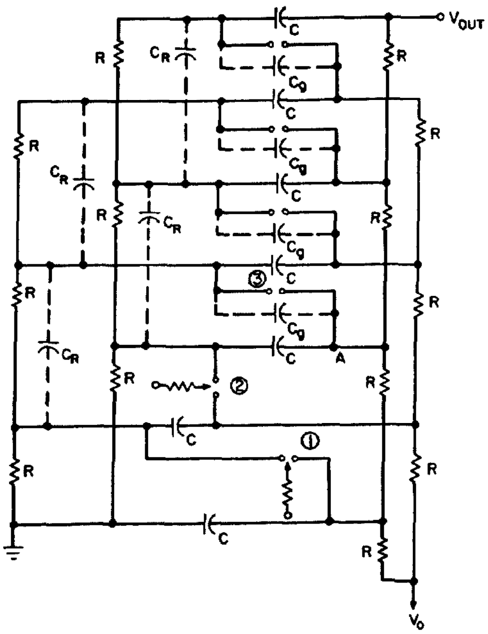

Figure 1. n=2 Marx Generator

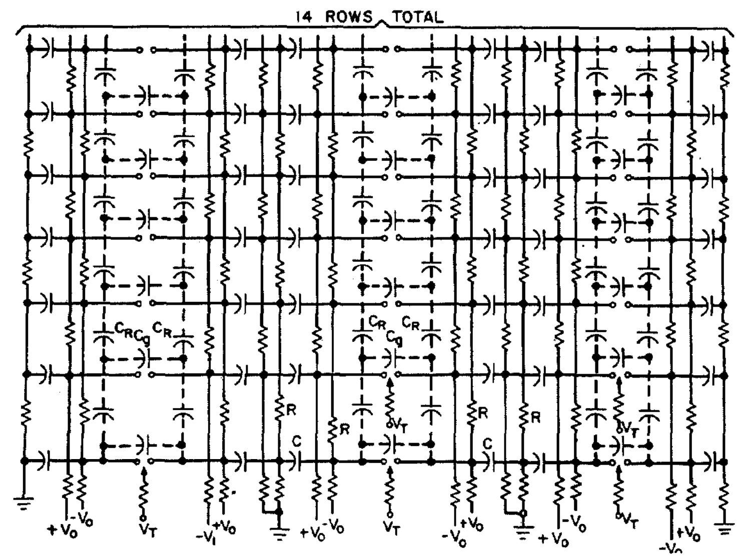

Figure 2. Type S Marx Generator

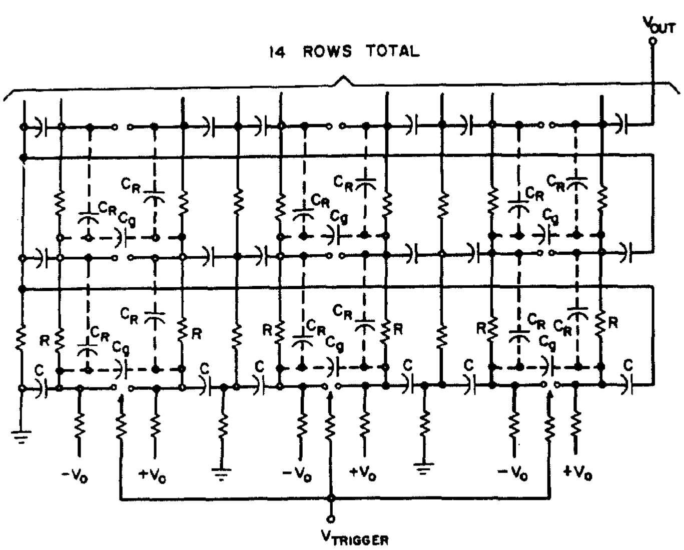

Figure 3. Type Z Marx Generator

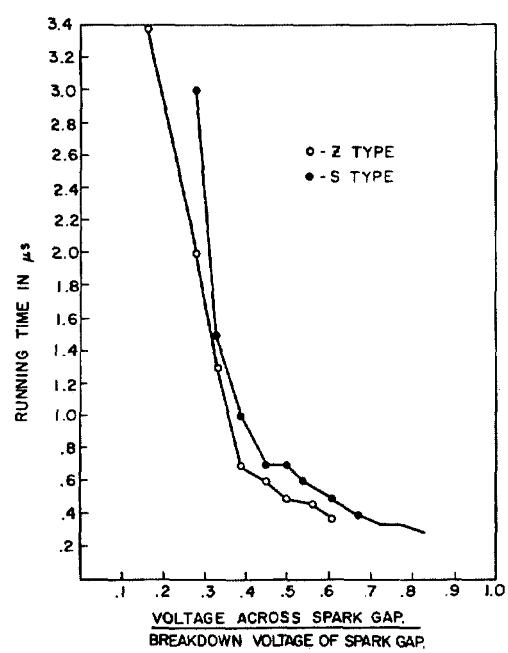

Figure 4. Switching Times for Model Marx Generators

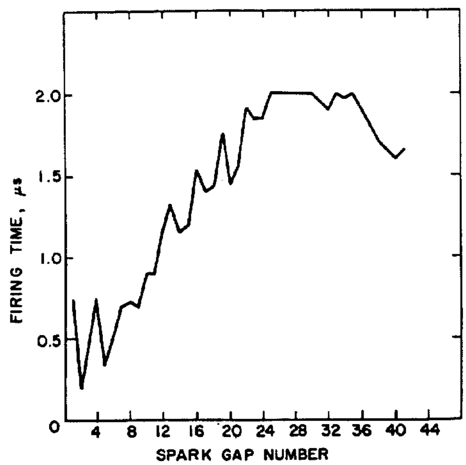

Figure 5. Gap Breakdown Vs. Time

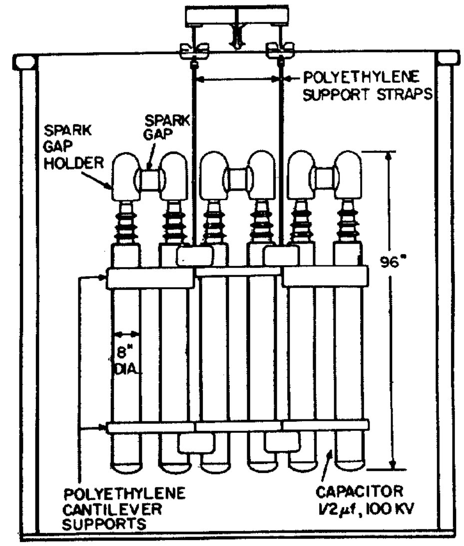

Figure 6. One Row of Hermes I Marx Generator

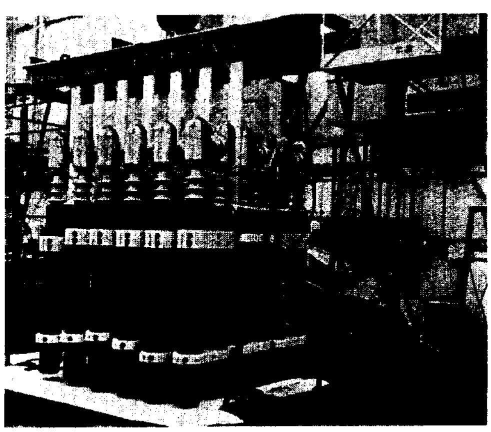

Figure 7. Hermes I Marx Generator

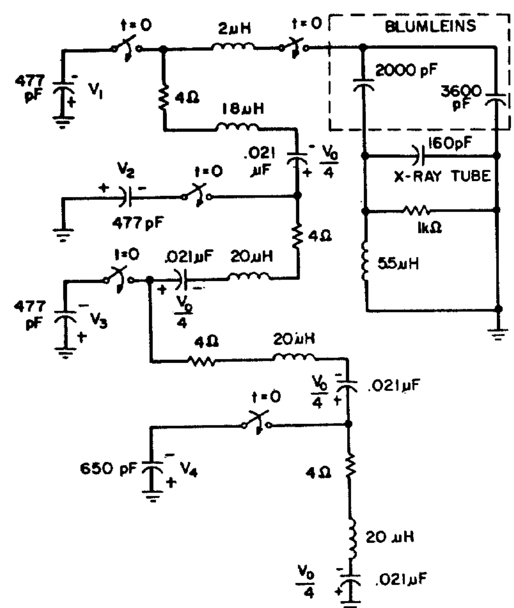

Figure 8. Hermes II Equivalent Circuit

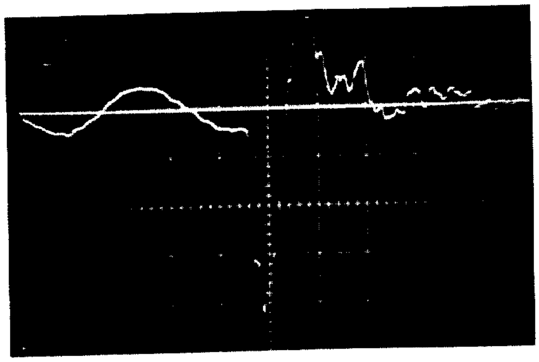

Figure 9. Hermes II X-ray Tube Voltage Trace (Large Prepulse)

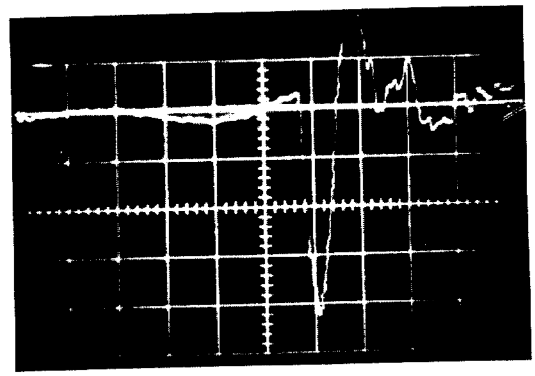

Figure 10. Hermes II X-ray Tube Voltage Trace (Small Prepulse)

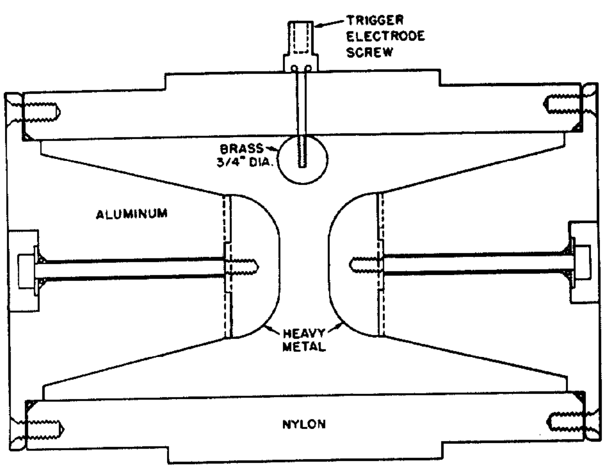

Figure 11. Hermes Spark Gap

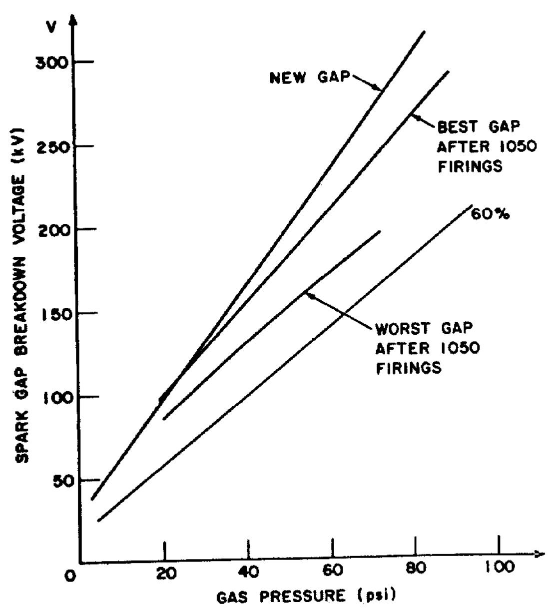

Figure 12. Hermes Spark Gap Breakdown Characteristics