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PERFORMANCE OF THE HERMES-III PULSE FORMING LINES*

J. A. Alexander, J. P. Corley, D. L. Johnson,
G. J. Denison, K. Hodge, P. Pankuch, J. J. Ramirez
Sandia National Laboratories
Albuquerque, New Mexico 87185

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ABSTRACT

Hermes III is a new 20-MV, 730-kA, 40-ns pulsed power accelerator.[1] In Hermes III, eighty pulse forming lines (PFLs) generate 1.1-MV, 220-kA pulses, which are then added in a series/parallel configuration to produce the desired output pulse.[2] Under normal Hermes-III operation, the PFLs produce a ~40-ns FWHM pulse with a ~15-ns, 10-90% rise time, and a one-sigma jitter of ~4 ns. The Hermes-III water-dielectric PFLs have undergone 18 months of testing. During this period, over 59,000 PFL-shots have been accumulated, most of these at or near peak power. The PFLs have met design specifications, and they have proven to be highly reliable. This paper presents a brief overview of the PFL design, together with a detailed discussion of the system performance and limitations during this extensive testing period. A modification to the PFLs to produce a ramped output pulse was designed and tested. Results indicate that a ramped output pulse can be produced using a stepped impedance PFL.

Introduction

Hermes III is a new gamma-ray simulator at Sandia National Laboratories. Figure 1 shows a drawing of Hermes III. Hermes III has ten oil-insulated Marx generators. Each Marx generator charges two intermediate energy storage water capacitors and each water capacitor charges four PFLs. Twenty SF_6-insulated, multi-stage, laser-triggered gas switches provide charging sychronization for the eighty PFLs.[3] The high voltage feeds from the gas switches to the PFLs have an inductance low enough to charge the PFLs to 2.2 MV in ~200 ns. The eighty PFLs deliver ~1.1-MV, 220-kA, 40-ns FWHM pulses to twenty inductive cavities, where their currents are added to produce twenty 1.1-MV, 730-kA, 40-ns pulses.[4] A magnetically insulated transmission line (MITL) adds the output voltage of the twenty cavities and delivers it to an electron beam diode.[5]

This paper gives a brief description of the PFL modules. The performance that is achieved under normal operating conditions on Hermes III is presented, together with design issues encountered during the past 18 months of testing. We discuss initial results of experiments to develop a pulse shaping capability for the Hermes-III PFLs.

PFL Description

A drawing of a PFL module is shown in Fig. 2. Each module consists of a set of coaxial 5-Ω transmission lines. The inner conductor is 16.8 cm in diameter, and the outer conductor is 35.6 cm in diameter. Each PFL module is made up of a pulse forming section, a peaking section, and an output transmission line section. It employs a pulse forming switch, a peaking switch, and a crowbar switch; all self-closing water gaps. The peaking switches provide the means to adjust the rise time of the output pulse. The crowbar switches are used to truncate the end of the pulse to set the pulse width for the diode. The crowbar also functions to suppress the pre-pulse voltage that is delivered to the output transmission lines.

The PFL conductors are made of stainless steel to ensure survival for several thousand shots against the large mechanical shocks generated by the self-closing water gaps. Access ports are located at the switch locations, with removable inserts that provide continuity to the outer conductor. These inserts are perforated to relieve overpressure due to the shockwaves generated by the water gaps.

The inner conductors are supported by two spoked barriers and two solid disk barriers. The spoked barriers have two metal rods, which extend between each of the spokes. This geometry reduces reflections due to impedance mismatches at the barriers, and also allows the entire PFL module to use a common volume of deionized water. The solid disk barriers also support the inner conductors, as well as provide the oil/water interfaces with the oil tanks and the cavities.

The output transmission line has a 25.4-cm section that can be relocated to the pulse forming section to add 15 ns to the pulse width, should this be desired. Increasing the pulse width in this manner would require the addition of a third row to the present Hermes-III Marx generators.

Hermes-III PFL Performance

The Hermes-III PFLs were developed in the Subsystems Test Facility (STF). The performance capability of these modules was described previously.[2] Figure 3 shows a sample waveform when the water switches have been optimized. The output waveshape is strongly influenced by reflections from various parts of the module, including the water switches. Figure 4 shows the variations in pulse shapes we obtain under normal operation from modules throughout Hermes III. The performance of the PFLs has not been optimized thus far, and produce an output pulse width of ~40 ns with a 10-90% rise time of ~15 ns. The initial peaking gap and crowbar settings are still being used. The radiation specifications have been met without optimizing the PFLs.

The PFLs were designed to be charged in approximately 200 ns, to produce a one-sigma jitter of <4 ns. Previous data from self-closing water switches show that the switch jitter is directly related to the PFL charge time.[6,7] Figure 5 shows a distribution of the first-to-last spread of the eighty PFL outputs obtained for a 245 shot sequence at full power. The spread of the twenty gas switches has also been measured for these shots,[8] and their contribution to the PFL output spread has been removed to first order. This was accomplished by assuming that the measured spread in the PFL outputs is due to both the gas switch and the PFL jitters. The PFL switch jitter is then given by

$$\sigma^2_{PFL} = \sigma^2_{OTL} - \sigma^2_{GS} , \qquad (1)$$

where σ_{OTL} and σ_{GS} are the measured rms jitters of the PFL output pulse and the gas switch respectively. The histogram in Fig. 5 is approximated by a Gaussian distribution with a mean of 18 ns and a sigma (standard deviation) of 3.5 ns. The pulse forming switches have not been adjusted to try to remove any systematics in the switching which might be occurring. Tests performed over a short sequence of shots indicate that the spread of the eighty output pulses can be maintained around a narrow band. with a mean spread of 17-18 ns by carefully adjusting the switch settings. The voltage pulse rise time requirement at the diode has been met without the need to make such adjustments, thus reducing the PFL maintenance required under normal operating conditions.

The deionized water in the PFLs is not recirculated in Hermes III. The stainless steel parts enable the water to remain above 10^5 $\Omega \cdot$cm for a period of over two weeks. The water is currently being replaced every other week, even though its still above 10^5 $\Omega \cdot$cm at the end of each cycle.

Some weld joints on the PFL inner conductors broke after a small number of shots. The manufacturer had not met weld penetration design specifications. The parts were rewelded to specifications, and no further failures have been observed.

The individual PFL moduless on Hermes III have as many as 730 shots on them. The vibrations produced by the shockwaves, from the self-closing water gaps, have caused the bolts on the PFLs to loosen, despite the use of lock washers. The entire set of PFLs have required retightening only once over the entire period. The pulse forming switches are surviving very well. Figure 6 shows a new pulse forming switch, and one with several hundred shots on it.

The original peaking switch design proved to be too weak to take the mechanical shocks. Figure 7 shows the damaged incurred by the peaking switches after several hundred shots. Also shown is the newly designed switch, which has been installed and is showing little damage.

The spoked support barriers have performed very well. No electrical breakdowns have occurred on these barriers. There have been seven barriers that failed mechanically. Figure 8 shows one of these failed barriers. All barriers have cracked at the same position along its circumference. A design modification has not been attempted, due to the small number of failures. The source of the stresses which cause the failures has not been determined.

The solid-disk oil/water interface barriers have failed in a number of modes. A number of barriers have tracked very lightly on the water side of the barrier. These barriers have been handled either by replacing them with a new barrier, resurfacing them, or leaving them alone. The resurfaced barriers seem to survive as well as a new barrier. Lightly tracked barriers have been left in the machine, with no performance degradation over several hundred shots. The lightly tracked barriers are believed to be the result of insufficient debubbling. Debubbling these interfaces is accomplished by striking the outer conductor with a dead blow hammer. Several barriers have failed because of arcing through the material from the inner conductor to the outer conductor, and have been penetrated from the water to the oil side. The barriers with the tracks through the material are believed to be the result of flaws in the material. Some heavy surface tracks have also been seen. Figure 9 shows a barrier tracked through the material, a resurfaced barrier, and a new barrier.

Ramped Pulse Experiment

Research is being done to apply Hermes-III technology to drive an ion-beam diode. As part of this effort, computer modeling and experiments are being conducted to produce a PFL which provides a ramped output pulse. A ramped pulse is desired to provide beam bunching and power amplification at the target. The ions, in the latter part of the pulse, are generated at a higher voltage. As the ion bunch is transported to the target, the ions with higher kinetic energy catch up with slower moving ions produced earlier in the pulse, thus resulting in a higher power, shorter pulse at the target. The PFL pulse shaping experiments are being performed at the Subsystems Test Facility (STF). STF was built to test full scale Hermes-III components during construction of Hermes III. The STF now provides us with a well-suited facility to perform tests using Hermes-III technology, since it is equivalent to one full Hermes-III module.

The initial experiment was performed using a stepped-pulse forming section that had a 20-ns, one-way transit time, and whose impedance varied from 4 Ω on the input end of the line to 6 Ω on the output, or switched end, of the line. The line was divided into three equal length segments of 4 Ω, 5 Ω, and 6 Ω. A sample waveform of the output PFL voltage is shown in Fig. 10(a). The next stage in the experiment was performed using a stepped-pulse forming section that had a one-way transit time of 27.5 ns, and whose impedance varied in three equal length steps from 3 Ω on the input end to 7 Ω on the output, or switched, end. A sample waveform of the PFL output voltage is shown in Fig. 10(b). Figure 11 shows the 3-5-7-Ω configuration. Notice that the 25.4-cm long outer conductor section mentioned earlier has been moved from the output end of the PFL to the input end to accommodate the longer pulse forming section.

In the case of the 4-5-6-Ω pulse-forming section experiment, the output voltage varied by about 25% from the start of the ramp to peak. In the case of the 3-5-7-Ω PFL experiment, the output voltage varied by about 35%. These results demonstrate that it is possible to control the slope of the ramp in our PFL designs.

Much work is yet to be done in understanding and controlling the reflections in the line to generate a linear ramp without the observed oscillations shown in Fig. 10. Figure 12 shows the simulated output pulse produced by a constant impedance, 5-Ω, 27-ns, one-way transit time PFL into a 5-Ω load. Also shown is the calculated waveform when the constant impedance PFL is replaced in the model by a continuously tapered impedance PFL, with a 3-Ω input and a 7-Ω output. Calculations show that the tapered PFL is as efficient in energy transport as the straight PFL.

Summary and Conclusions

The Hermes-III PFLs are performing reliably. The PFLs are producing a 1.1-MV, 40-ns FWHM, ~15-ns, 10-90% rise time pulse, with which Hermes III has met all of the radiation specifications for which it was designed. The PFL modules are capable of producing an ~8-ns, 10-90% rise time, which gives Hermes III added capability if needed.

The issues encountered with the PFLs have not hampered the machine in meeting its shot rate goals. Hermes III was designed to shoot 600 shots per year, at a rate of 3-5 shots per day. It met specifications and became operational one year ahead of schedule. Hermes III routinely fires 8-9 shots per day, at ~30 minute intervals.

Initial results on STF using stepped-impedance PFLs demonstrate the capability of producing a ramped voltage pulse on Hermes III. Further work is required to fully develop this capability.

Acknowledgments

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Figure Captions

Fig. 1 Drawing of Hermes III

Fig. 2 Cut-out view of PFL module

Fig. 3 Sample output waveform produced with optimum switch settings

Fig. 4 Sample waveforms showing pulse shape variations from different PFL modules

Fig. 5 First-to-last timing spread for the 80-PFL modules observed over a 245 shot sequence

Fig. 6 Photograph of a new PFL switch electrode and of one with several hundred shots on it

Fig. 7 Photograph of damage done to the original peaking switch electrodes together with a new, modified electrode

Fig. 8 Photograph of a cracked spoked-barrier

Fig. 9 Photograph of a tracked, a resurfaced, and a brand new barrier

Fig. 10 Sample waveforms produced by stepped-impedance PFLs. (a) Using the 4-5-6-Ω configuration. (b) using the 3-5-7-Ω configuration

Fig. 11 Sketch of the 3-5-7-Ω, stepped PFL configuration

Fig. 12 Simulated waveforms produced by (a) a constant impedance PFL, and (b) a continuous tapered-impedance PFL

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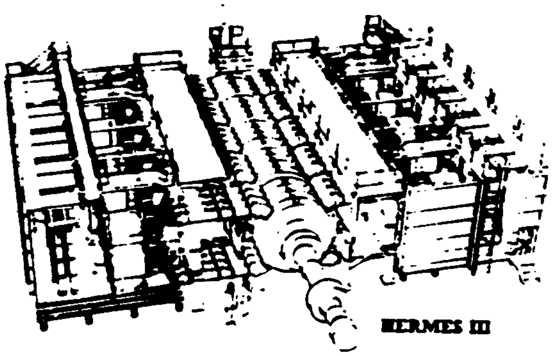


Fig. 1. Drawing of Hermes III.

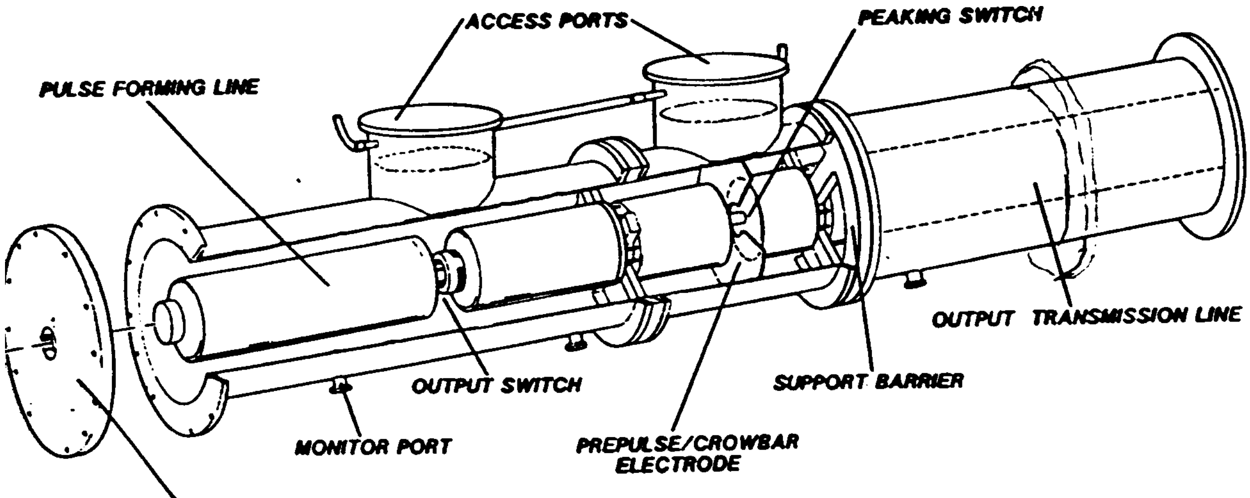
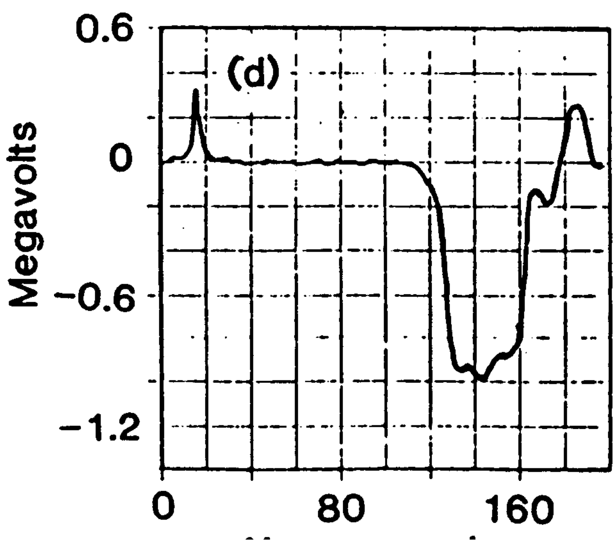


FIGURE 2

CUT-OUT VIEW OF A PFL MODULE



SAMPLE OUTPUT WAVEFORM PRODUCED WITH OPTIMUM SWITCH SETTINGS

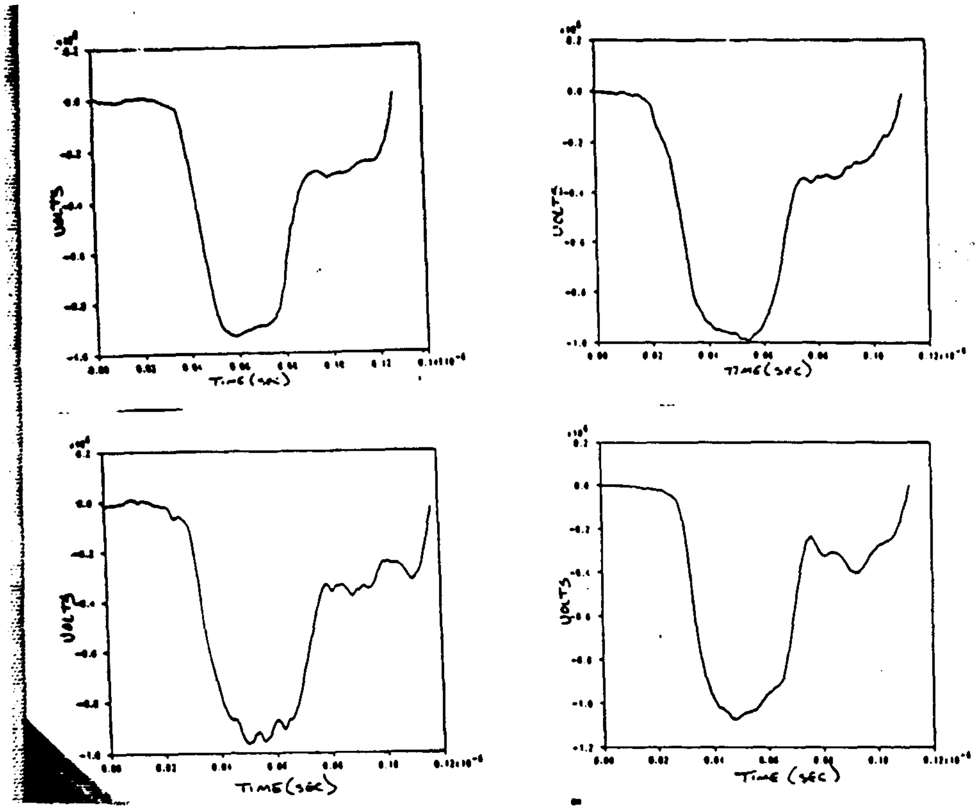


FIG. 4

SAMPLE WAVEFOR[illegible] SHOWING PULSE S[illegible] VARIATIONS FROM DIFFERENT [illegible]

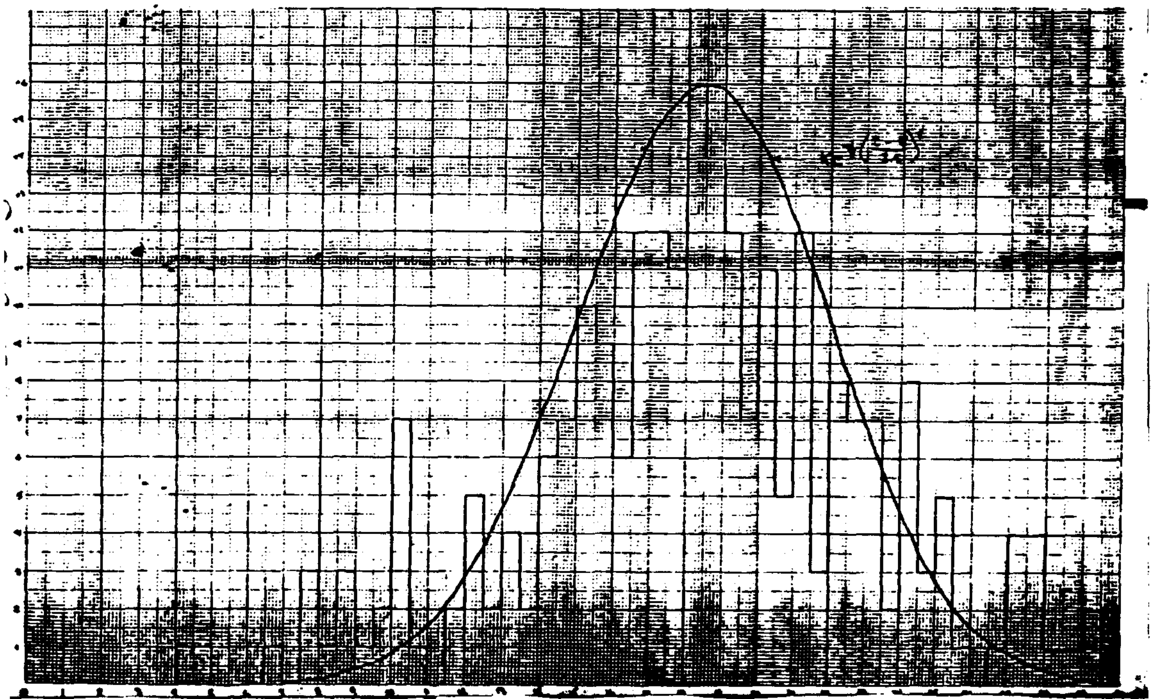


FIG. 5

SPREAD

FIRST-TO-LAST TIMING SPREAD FOR THE EIGHTY PFL MODULES OBSERVED OVER A 245 SHOT SEQUENCE

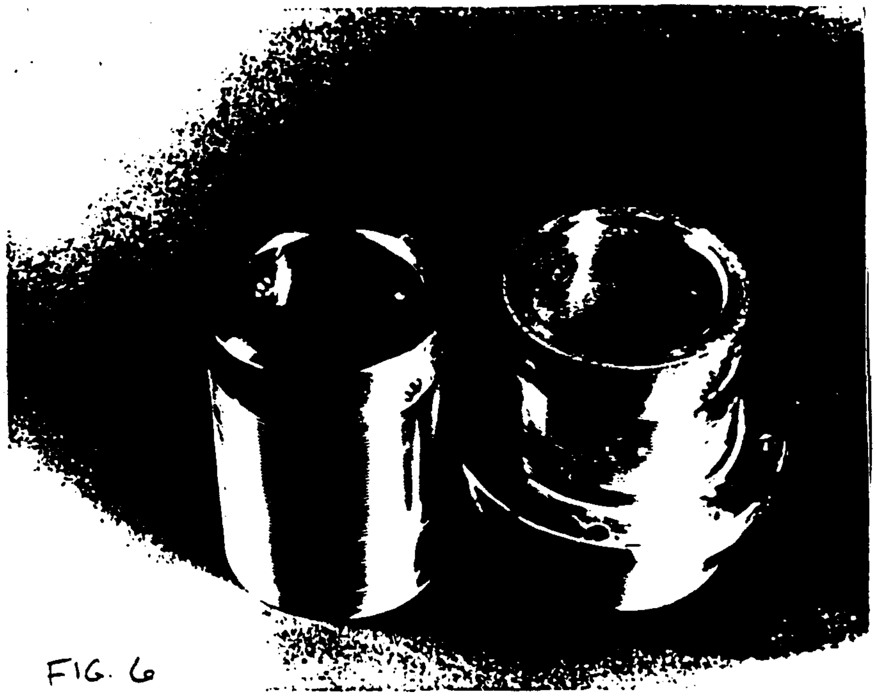


FIG. 6

PHOTOGRAPH OF A NEW [illegible] SWITCH ELECTRODE [illegible] ONE WITH SEVERAL [illegible] SHOTS ON IT.

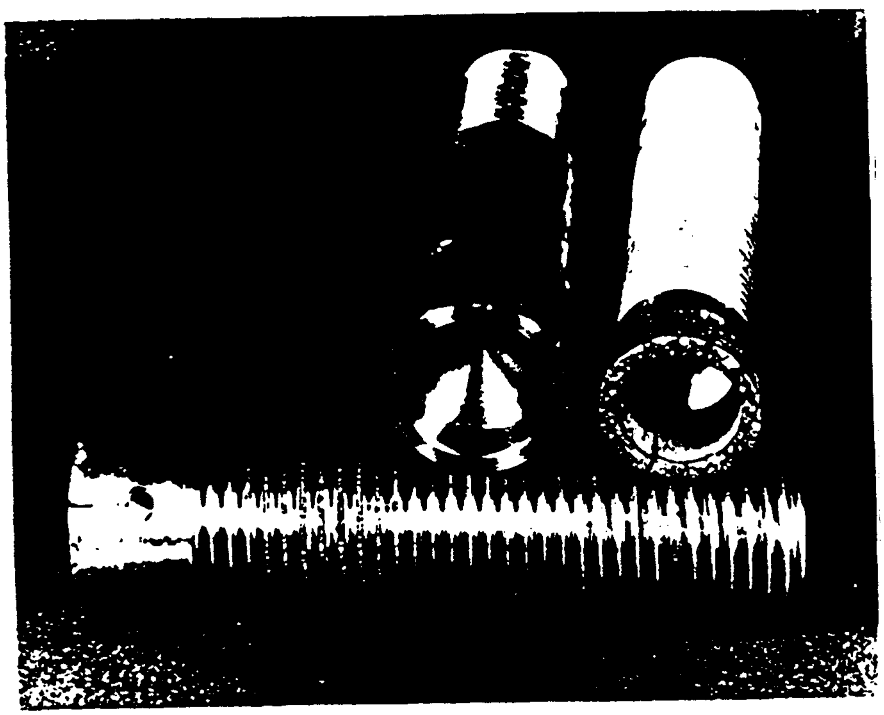


FIG. 7

PHOTOGRAPH OF DAMA[illegible] TO THE OR[illegible] SWITCH ELECTRO[illegible] WITH A NEW, MODIFIED ELECTRODE.

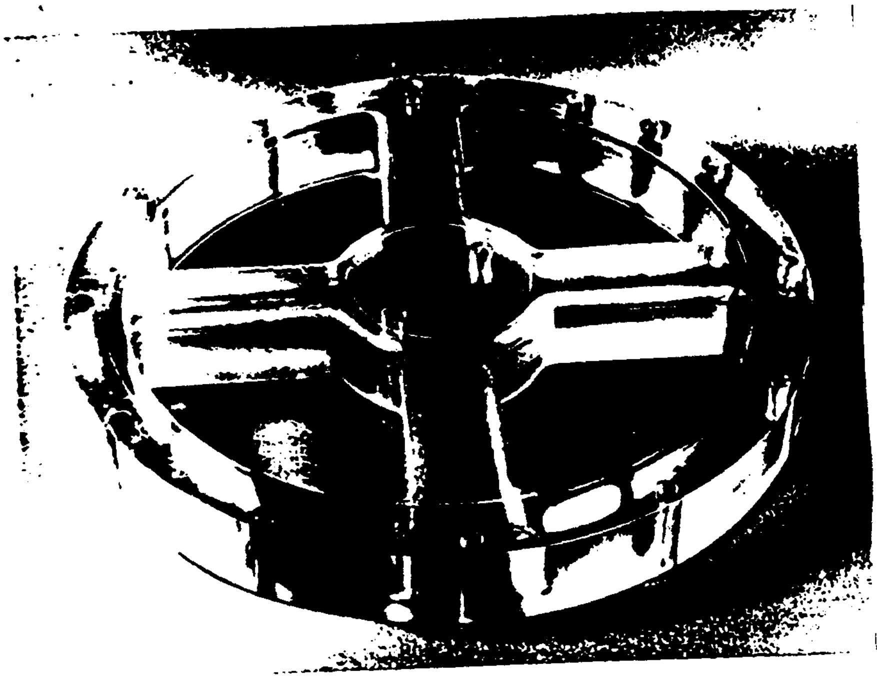


FIG. 8

PHOTOGRAPH OF A CRACKED SPOKED-BARRIER.

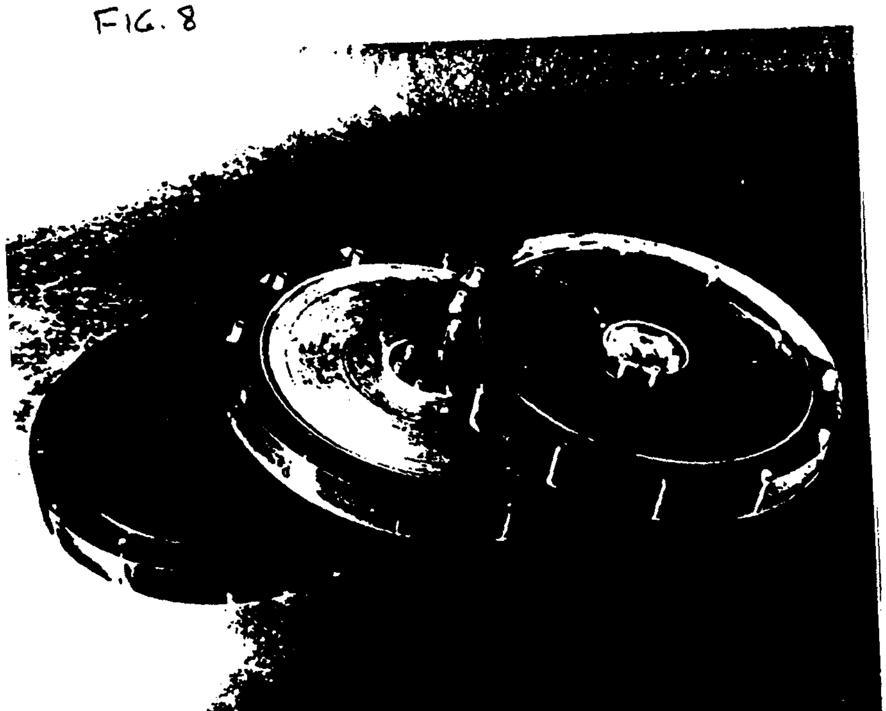
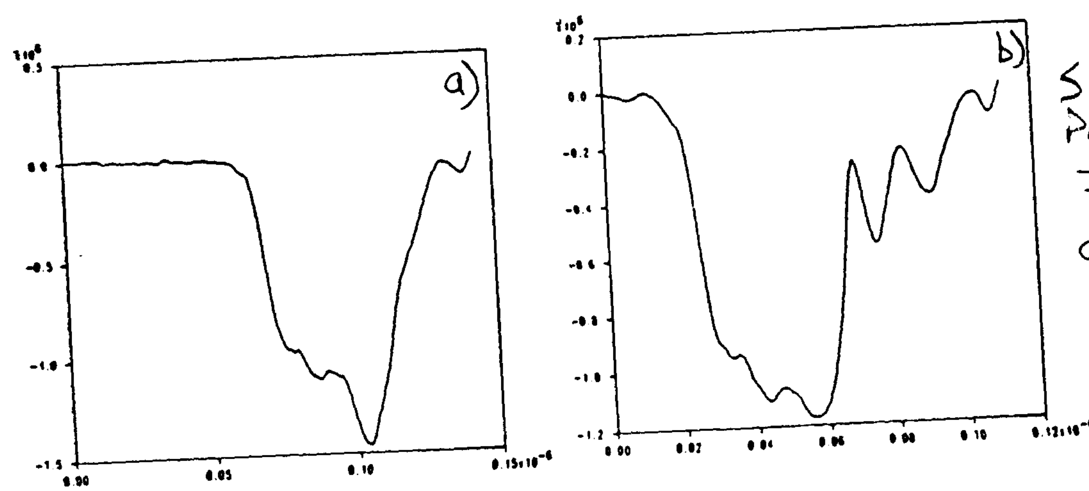


FIG. 9

PHOTOGRAPH OF A TRACKED, A RESURFACED AND A BRAND NEW BARRIER.



SAMPLE WAVEFORMS AS PRODUCED BY STEPPED-IMPEDANCE PFLs.

a) USING THE 4-5-6 Ω CONFIGURATION.

b) USING THE 3-5-7 Ω CONFIGURATION

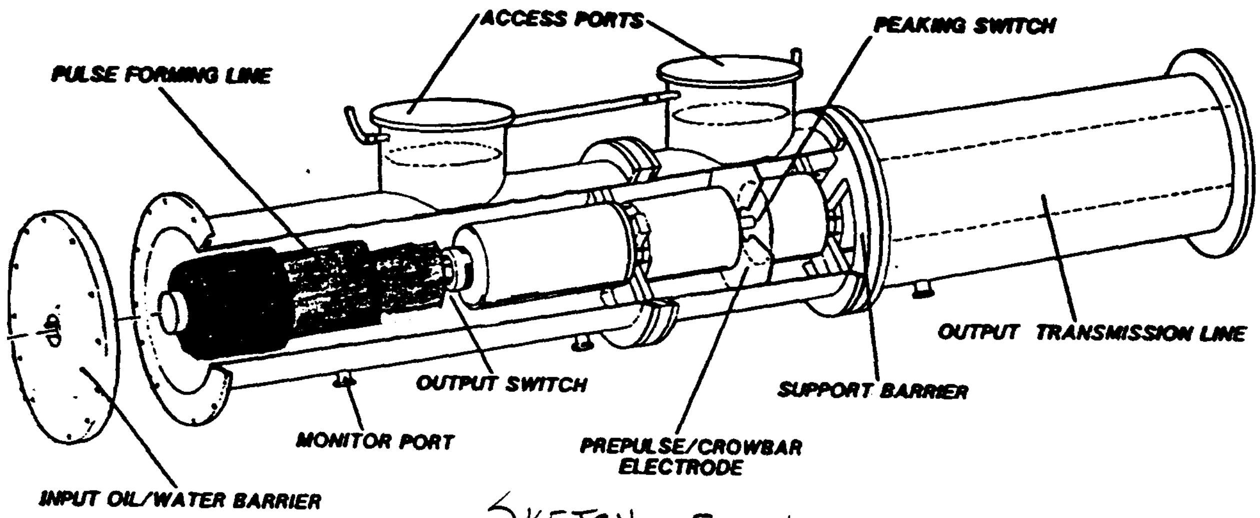


FIG. 11 SKETCH OF THE CONFIGURATION 5-5-7 Ω, STEPPED PFL

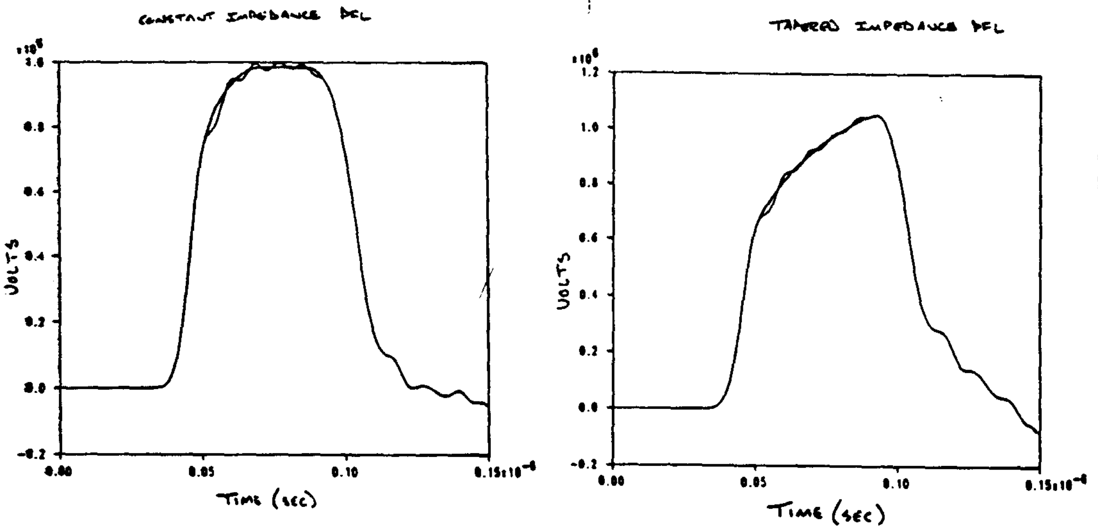


FIG. 12 SIMULATED WAVEFORMS PRODUCED BY

a) A CONSTANT IMPEDANCE PFL

b) A CONTINUOUS TAPERED-IMPEDANCE PFL