

# MODIFICATION OF AN EMP FACILITY TO SUPPORT THRESHOLD TESTING OF ELECTRONIC SYSTEMS

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## Abstract

The Naval Ordnance Transient Electromagnetic Simulator (NOTES) is a bounded wave test facility located at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD). NOTES was designed to enable standardized Electromagnetic Pulse (EMP) testing, but in order to support tests to assess the vulnerability of US infrastructure to High-altitude EMP (HEMP) it was modified to enable threshold testing with peak amplitudes of 1 kV/m up to 100 kV/m while maintaining nominally the same temporal characteristics of the threat waveform. The range of amplitude was accomplished using three different voltage pulser configurations which provided nearly continuous variability. This paper provides a detailed description of the NOTES facility and the design, implementation, and results of these modifications. We present the waveforms that were used during testing and show that they provided a consistent stimulus both in terms of the overall waveform shape and in the critical risetime characteristic.

## I. BACKGROUND

Study of the effects on electronics from the EMP generated by a nuclear weapon has decreased with the cessation of the Cold War, but this decline coincides with the increasing reliance on digital electronics for the civilian infrastructure. A recent Congressional Commission was formed to investigate the vulnerability of modern US infrastructure to the potential impact of the EMP generated by a high altitude nuclear weapon burst, commonly referred to as HEMP. The default free-field HEMP environment is detailed in MIL-STD-464 and is a double exponential waveform with peak amplitude of 50 kV/m, rise-time of roughly 5 ns, and fall-time of greater than 30 ns. Standard HEMP test requirements are based on the premise that a piece of equipment or facility is hardened and shown to survive the standard waveform, but this provides no insight into the threshold at which effects might occur, especially in modern digital systems not specifically hardened against HEMP.

The Directed Energy Technology Office (DETO) was funded by the Congressional EMP commission to help evaluate the potential impact of HEMP on various critical

infrastructure systems. In previous work by DETO to investigate the vulnerability of electronics to Radio Frequency Weapon threats, a series of Marx bank pulsers was used in an indoor Bounded Wave Structure (BWS) to perform susceptibility testing over a wide range of electric field levels. Specifically, two single stage sources, two 8 stage Marx sources and one 25 stage Marx source were used to provide peak transient electric field levels ranging from 800 volts/meter to 90 kV/meter. Based upon that experience, a similar approach was pursued for the EMP commission effort by modifying an existing outdoors bounded wave EMP facility which had a working volume large enough to support the test goals.

## II. NOTES FACILITY

The NOTES facility at NSWCDD is shown in Figure 1. It was built in 1992 to enable EMP testing with a fixed vertically polarized peak output of 50 kV/m in a working volume with 10 meter maximum height. In 1996 the Marx generator used as the pulse source was modified to enable continuous variation of the peak electric field in the working volume from 50-100 kV/m.

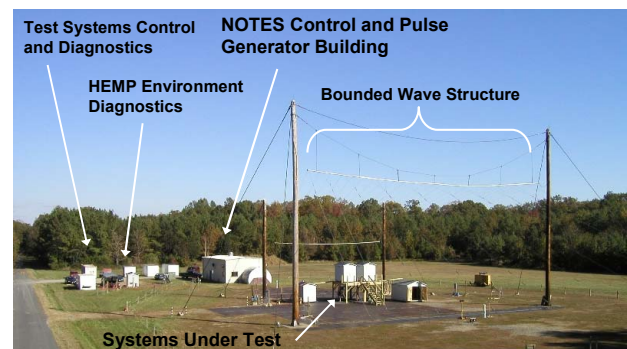


Figure 1. NSWCDD NOTES facility

In order to achieve these peak levels with a 10 meter working height, a fast rising pulse generator delivering 500kV to 1 MV into the 100 ohm impedance of the BWS is required. This is accomplished with a slow Marx generator that charges a fast peaking circuit, as shown in the schematic of Figure 2.

The Marx is a slightly modified stacked tray Maxwell design, circa 1980, housed in an oil-bath which serves multiple purposes. The oil isolates the components of the

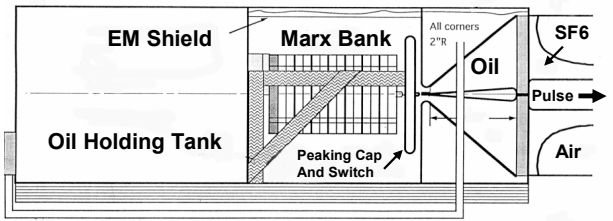
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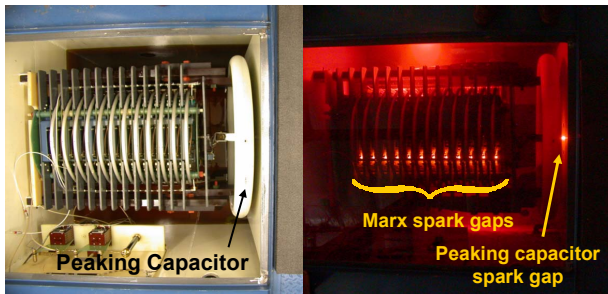
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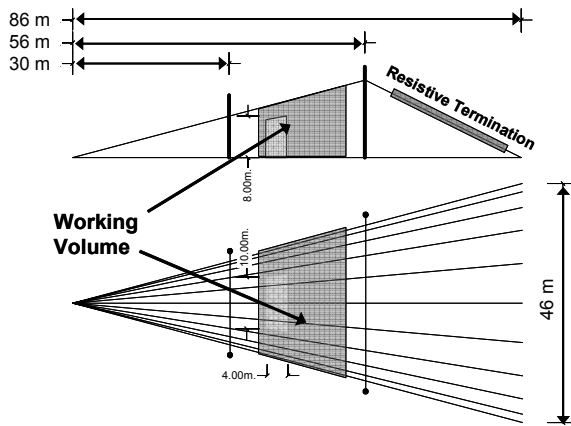
Marx trays, provides enhanced capacitance for the 54 inch diameter peaking capacitor, and acts as the breakdown medium for the peaking switch. Figure 3 shows the 12-tray, 24 stage Marx generator installed in the generator housing and operating while immersed in oil. Each stage of the Marx consists of a 220 nF capacitor, so the overall erected capacitance is slightly less than 10 nF. The peaking capacitor has a value of 240 pF in oil.



**Figure 2.** Schematic of high voltage pulse generator, including Marx, peaking capacitor and switch, impedance transition, and pulse launch into the BWS.



**Figure 3.** Pictures of 24 Stage Maxwell Marx Generator as installed (left) and when operated in oil (right). Only one spark gap per tray is visible in the picture.

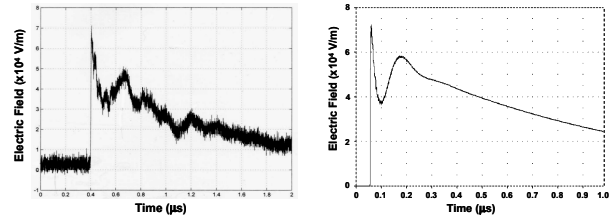


**Figure 4.** Layout and dimensions of NOTES bounded wave structure.

The output of the pulse generator is injected into a SF6 and/or air insulated zipper balun which provides a high-quality transition from the coaxial symmetry of the peaking circuit to the parallel plate geometry of the BWS, which is shown in Figure 4. The BWS was built to represent roughly constant 100 ohm transition line impedance. It accomplishes this with a wire structure

which emerges from the Marx generator/control building after the balun and rises gradually to a height of 10 meters over a length of 56 meters, while simultaneously fanning out to a width of roughly 20 meters. The BWS is terminated in a distributed chain of 1 k-ohm resistors in a series-parallel configuration to match the 100 ohm transmission line and reduce reflections.

Figure 5 shows a typical output waveform measured in the working volume of the BWS. All electric field measurements reported in this paper were made with either EG&G ACD-10 D-dot probes and integrating fiber optic links, or Nanofast EFS 709-1 direct measuring field probes. All probes, links, and oscilloscopes had bandwidth greater than 150 MHz.

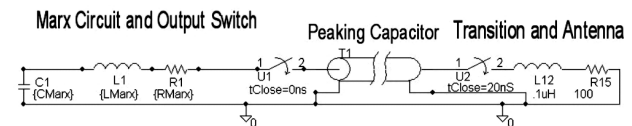


**Figure 5.** Graph of typical NOTES EMP output waveform (left) and PSPICE simulated output (right).

### III. NOTES MODIFICATIONS

Although NOTES as described above performed satisfactorily for standardized EMP testing, it was not flexible enough to provide the very low peak field levels necessary to determine the onset threshold of effects on electronics. We desired to reduce the peak level as low as 1.5 kV/m without altering the salient characteristics of the EMP simulated waveform. Specifically, the goal was to have the capability of generating peak fields of approximately 1.5, 3, 6, 15, 25, 50, and 100 kV/m.

A simple PSPICE circuit analysis of the NOTES system was developed to aid in the system modification and is shown in Figure 6. A lumped approximation was used to represent the Marx generator with an L of 0.5  $\mu$ H, a C of 10 nF, and an internal resistance of 0.5 ohms. A 10 ohm transmission line segment of appropriate length was used to simulate the action of the peaking capacitor. Two switches simulate the turn-on of the Marx at  $t=0$  and the firing of the peaking switch 20 ns later.

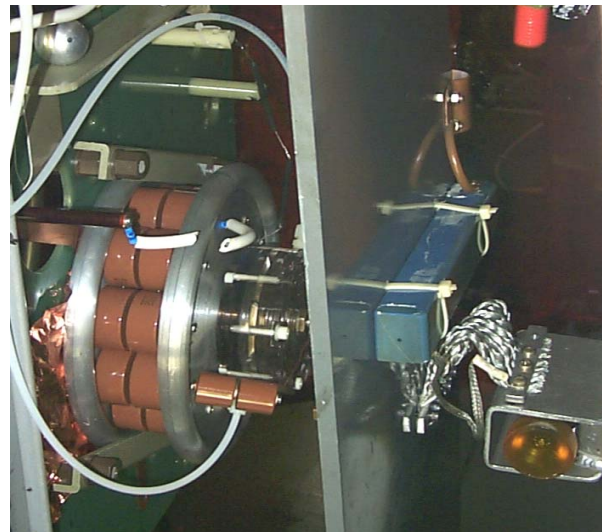
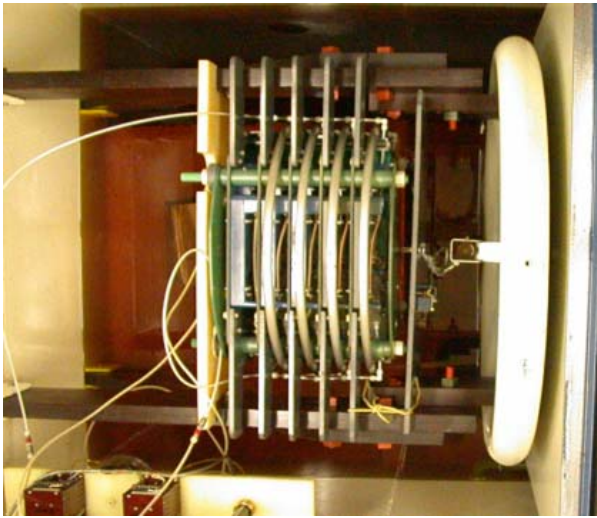


**Figure 6.** PSPICE circuit model for NOTES.

The right graph of Figure 5 shows the simulated PSPICE output and it is clear that the calculation reproduces several of the salient features of the experimental waveform, including the fast rise-time of the peaking circuit and the fast fall-time of the initial pulse before the second rise corresponding to the slower action of the Marx generator.

Given a reasonable circuit simulation of the existing NOTES operation, we used PSPICE to help us design voltage pulse generators capable of producing the lower voltages necessary to achieve lower fields in the BWS while still maintaining pulse shape fidelity.

To produce intermediate levels of 15 to 35 KV required a Marx with an equivalent erected capacitance of roughly 10 nF and an output voltage of 150 to 350 KV. This was accomplished by removing all but 4 trays of the existing Marx to reduce the number of stages from 24 to 8. For the output capacitance to remain 10 nF required that the capacitors be 1/3 the value of the value of the capacitors in the original Marx configuration, which was accomplished by changing the capacitors on the 4 remaining trays from 220 nF to 80 nF. The top picture in Figure 7 shows this configuration mounted in the oil tank.



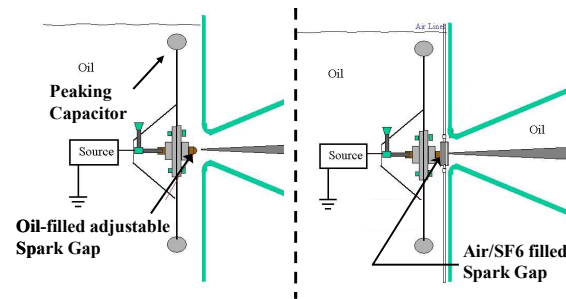
**Figure 7.** Pictures of 8-stage Marx mounted in empty oil tank (top) and single-capacitor equivalent assembly mounted in the empty oil tank next to the peaking switch adjustment mechanism (bottom).

It was more complex to develop the lower voltage pulser given the constraint of installation in the oil-filled

high voltage tank. This was necessitated by the fact that the oil-filled tank was also part of the output transmission line and hence altering this arrangement would have made it difficult to maintain the pulse characteristics.

To solve this problem, we built a 10 nF single-capacitor equivalent assembly from a series/parallel configuration of twenty 40 kV/2nF ceramic doorknob capacitors, shown in Figure 7, bottom photo. This was installed in place of the Marx generator trays and was charged to between 15 and 100 kV by a programmable power supply. The voltage was ramped slowly (seconds time scale) until a 100 kV spark gap self-triggered, discharging the capacitor into the peaking capacitor. Variation of gas type and pressure was used to set the operating point.

The requirement to operate in the oil-bath meant that the original peaking spark-gap was nearly impossible to breakdown at these low voltages. This was resolved by lowering a series of gap-separation modified Maxwell 100 kV spark gaps into the space between the peaking gap electrodes and adjusting the electrodes until they pinched the spark gap housing, making appropriate electrical contact. This is shown schematically in Figure 8. Again, variation in gas type and pressure were used to optimize the operating characteristic.

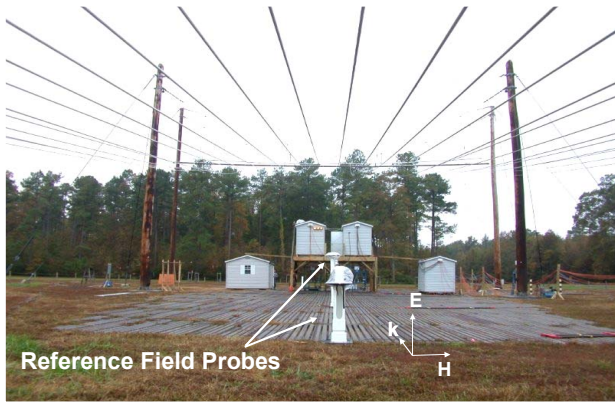


**Figure 8.** Schematic showing oil-filled peaking spark gap (left) and the same gap incorporating an air or SF6-filled commercial spark gap (right).

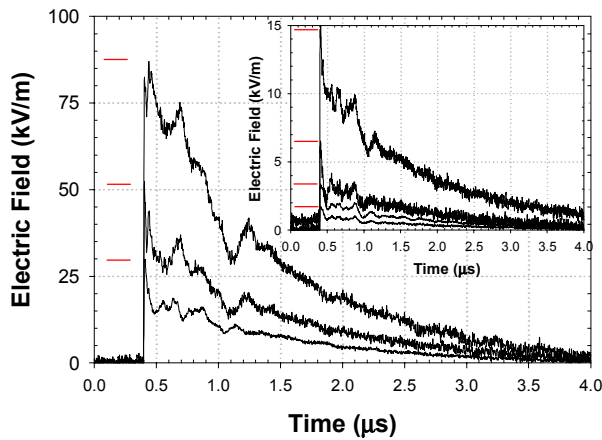
Changeover from the 24 stage Marx configuration to the 8 stage Marx required about 3 hours, including the time to drain and refill the oil in the Source Tank. The swap-out from the 8 stage Marx to the Single stage Marx took about the same amount of time, although with some added complexity because the power supply connections had to be changed as well.

#### IV. EXPERIMENTAL RESULTS

All of the configurations for NOTES we describe in this paper were used to support testing in the fall of 2003 for the Congressional EMP commission. Figure 9 shows a view looking from the Marx generator/control building toward the test volume. Visible in the picture are several electric field probes and the structures in the test volume which housed the test objects. Also visible in the picture are the wires which make up the upper electrode of the parallel plate transmission line of the BWS.



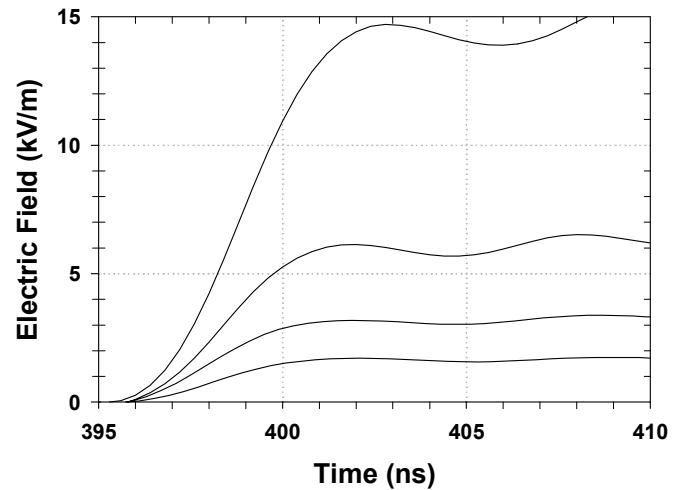
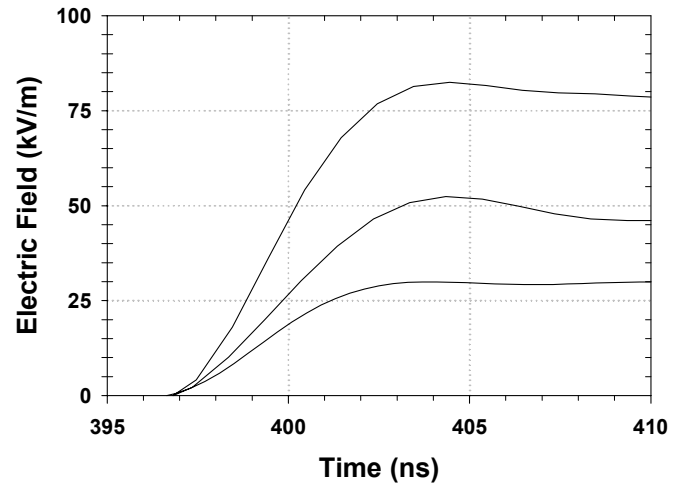
**Figure 9.** Photograph of the electric field probes and test-object structures inside the BWS as seen from the generator and control building.



**Figure 10.** Graphs showing peaks and overall waveform shape for 80, 50, 30 kV/m settings (main graph), as well as 15, 6, 3, and 1.5 kV/m settings (inset graph).

Experimental measurements of the waveforms delivered to the test volume are shown in Figure 10. The peak values of each level are difficult to separate because of the overlapping traces, so the peaks are denoted by the horizontal line-mark at the left of each trace. Note that the waveform character stays very consistent as the amplitude is varied with the 3 different pulse generators. This is also verified by spectral analysis of each waveform which we do not show here due to space limitations.

It is generally considered important to achieve a fast risetime for an EMP simulator. Figure 11 shows the same waveforms of Figure 10 with finer temporal resolution and focus on the leading edge of the traces. It is apparent that in all cases the risetime is between 5 and 7 ns, which was satisfactory for our testing purposes.



**Figure 11.** Waveforms showing risetime characteristics for 30, 50, and 80 kV/m peak levels (top) and 1.5, 3, 6, and 15 kV/m peak levels (bottom)

## V. SUMMARY

The NOTES facility at NSWCDD has been used for standardized EMP testing for more than a decade. Recent modifications to the facility have enabled us to successfully demonstrate the generation of a consistent EMP waveform across a span of peak fields from 1.5 to 100 kV/m. This capability was used to support threshold testing of the susceptibility of infrastructure electronics in support of a report to the congressional EMP commission.

## VI. REFERENCES

- [1] Report of *The Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack*, Volume 1, Executive Report 2004

## VII. ACKNOWLEDGEMENTS

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