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Electromagnetic Test Facilities at Sandia National Laboratories

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Abstract – *Described below are major electromagnetic test facilities at Sandia National Laboratories; each has undergone recent upgrades. This paper will discuss each facility, their uses, and upgrades pertaining to the facilities performance and diagnostic capabilities. The facilities discussed here are the Sandia Lightning Simulator, the Electromagnetic Environments Simulator, the Mode-Stirred Chamber, and Anechoic Chamber. Sandia's expertise in electromagnetics also extends to theoretical analysis and modeling, which can be done in conjunction with tests or experiments.*

Keywords – *testing, facilities, lightning, mode-stirred chambers, anechoic chambers, TEM cells*

I. INTRODUCTION

Sandia National Laboratories maintains a strong core competency in electromagnetic environments through a combination of experimental facilities, theoretical analysis, and computer-based modeling and simulation. A broad variety of problems can be addressed through testing, analysis, or modeling, or any combination of the three. The modeling capabilities will be briefly discussed; however, the main focus of this paper is the major experimental facilities, their uses, recent upgrades, and diagnostic capabilities.

II. SANDIA LIGHTNING SIMULATOR

The Sandia Lightning Simulator (SLS) allows equipment under test to be subjected to simulated lightning currents up to extremely severe levels. In reality, a lightning flash can consist of multiple lightning strokes. The SLS can be configured to produce either one or two simulated strokes, with or without continuing current. It can deliver a maximum peak current of 200 kA for a single stroke, 100 kA for a subsequent stroke, and several hundred Amperes of continuing current for hundreds of milliseconds. The performance characteristics are listed in Table 1, and a typical SLS single stroke is shown in Figure 1.

Test environments include direct-attachment lightning, (where the simulator is connected to or arcs to the test object), burn-through (which incorporates continuing current), and nearby magnetic fields due to the strokes. The SLS can be used to certify or evaluate hardware or to perform research. Historically, it has been mostly used for safety qualification testing of nuclear weapon components and weapon systems. However, it has also been used for basic research such as burn-through studies of different materials [1].

A picture of the main components of the SLS is shown in Figure 2. The simulated lightning strokes are generated by high-voltage Marx banks (up to 1.6 MV) that are housed in two large oil tanks for high-voltage insulation. The peak current can be varied depending on the charge voltage of the Marx banks. Triggered crowbar switches in each tank are used for pulse shaping and ultraviolet lasers trigger the crowbar switches at a predetermined time. Continuing current, when required, is delivered by a large motor-generator set.

Table 1. Performance Characteristics of the Sandia Lightning Simulator

Peak current	200 kA, max (single-stroke)
Current rate of rise	200 kA/us, max
Pulse width (@50% level)	50 to 500 us (dependent on load impedance)
Number of pulses	1 or 2
Interval between pulses	variable
Continuing current	100s A for 100s of ms

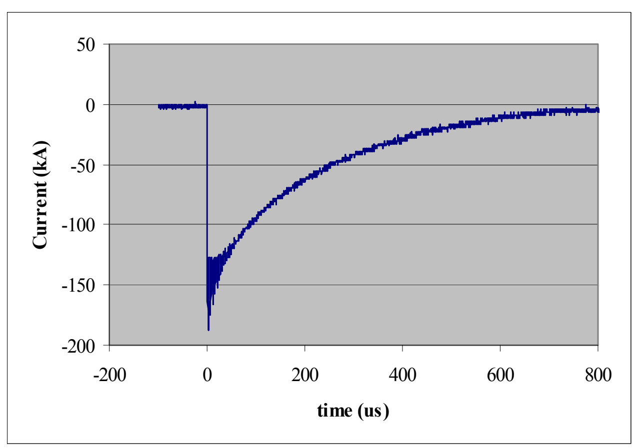

Figure 1. Typical SLS Single-Stroke Output.

A. Sandia Lightning Simulator Upgrades

Previously, a large Krypton-Fluorine ultraviolet laser was used to fire both crowbar switches. The laser light was split and routed to each tank with mirrors. This laser was replaced with two much smaller, less hazardous YAG lasers. The previous laser took up a small room, required handling and venting of toxic gas, and routing of exposed high energy laser light. Now, each oil tank has its own laser contained in an electromagnetically shielded box on the side of each tank, without exposed laser light or toxic gas.

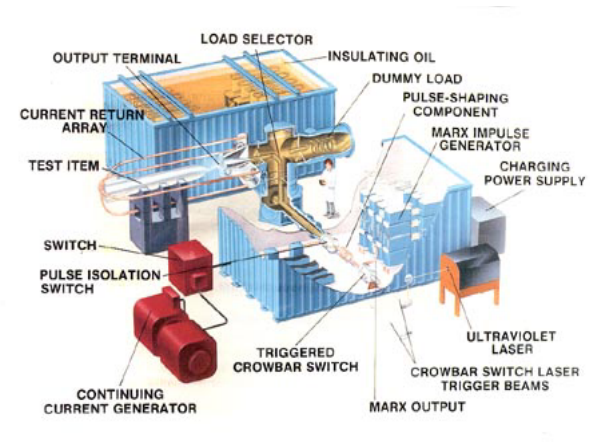

Figure 2. The Sandia Lightning Simulator.

The original low-voltage trigger system was replaced with up-to-date trigger generators that are remotely set and adjusted through a custom Labview program. The low-voltage trigger system initiates the firing of the high-voltage Marx banks, the lasers for the crowbar switches, and the continuing current generator.

The building that houses the simulator was updated to meet current environmental and safety regulations. Upgrades are planned for the extensive gas system which supplies high-voltage insulating gas to the many switches in the simulator and for automating the high-voltage control console. The high-voltage control console sets and monitors the gas system pressures, the high voltage power and trigger supplies, the continuing current generator operating parameters, and interfaces to building safety interlocks. Future upgrades include replacing the continuing current generator and installing an electromagnetically shielded video system to monitor test objects during testing.

B. Sandia Lightning Simulator Diagnostic Capabilities

The data acquisition system was also modernized to include Tektronix TDS 7054 oscilloscopes that have multi-frame capability for the double-pulse mode and a custom Labview program to set the scopes and retrieve data. Three oscilloscopes are dedicated to the simulator diagnostics, three are dedicated for customer use, and one oscilloscope is set aside as a spare for either use.

Simulator diagnostics include current and voltage measurements taken for each shot, which are sent back to a screen room via shielded coaxial cables. Three current viewing resistors in line with the simulator's return path measure the total current for each shot. A current viewing resistor is also used to measure the current inside each oil tank. The high-voltage trigger generator signals are monitored with a combination of current transformers and current viewing resistors. The crowbar voltage is measured with a resistive divider, and the low-voltage trigger signal to the crowbar switch lasers is monitored. It is important to monitor these signals. The timing between the peak Marx bank currents and the triggering of the crowbar switches is critical to achieving the desired peak current and protecting the high voltage components from damage due to potential large oscillations in the current pulse.

To minimize coupling from the electromagnetic noise generated during a shot, test object diagnostics are shielded in a metal instrumentation barrel. Their signals are fed through a fiber optic system back to the screen room. Pictures of the instrumentation barrel and fiber optic transmitters can be seen in Figures 3 and 4. Typical diagnostics are current viewing resistors and transformers, Rogowski coils for measuring current derivatives, and voltage dividers. Other compatible diagnostics are pressure transducers, temperature sensors, and electric and magnetic field sensors (D-Dot and B-Dot, respectively).

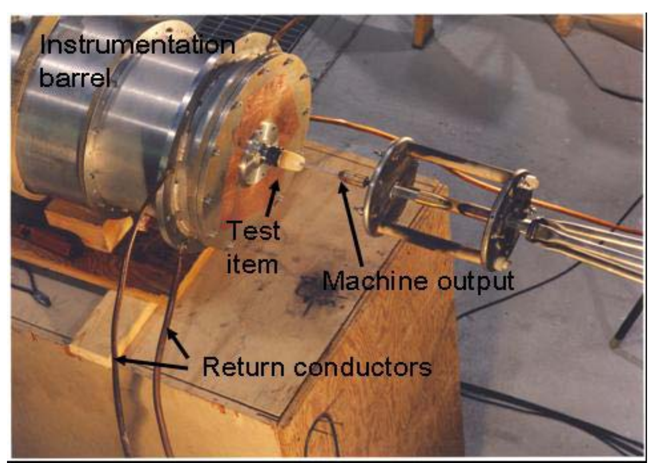

Figure 3. Instrumentation Barrel for Test Item Diagnostics.

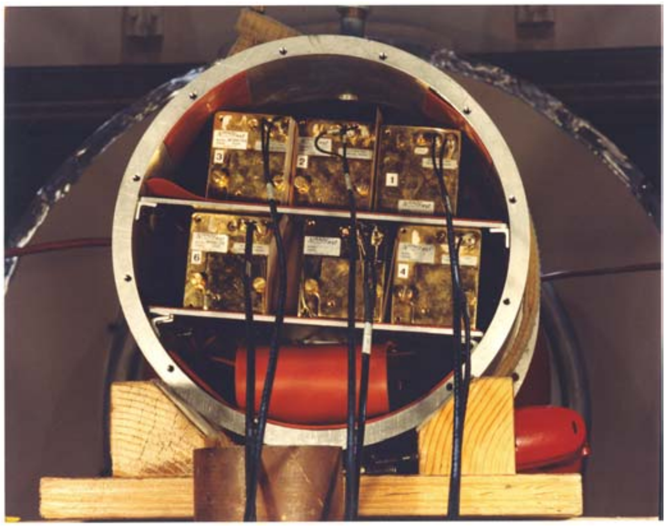

Figure 4. Fiber Optic Transmitters inside the Instrumentation Barrel.

III. ELECTROMAGNETIC ENVIRONMENTS SIMULATOR

The Electromagnetic Environments Simulator (EMES) is a large transverse electromagnetic (TEM) cell that propagates a uniform, planar electromagnetic wave through the working volume where test items are placed. EMES can be used for continuous wave (CW) Electromagnetic Radiation (EMR) and transient Electromagnetic Pulse (EMP) testing. The electric field is vertically polarized between the center conductor and the floor. If it is desired to illuminate test objects at different polarizations, the test object can be rotated. Its performance characteristics are listed in Table 2 and a picture of the whole facility is shown in Figure 5.

EMES has typically been used in the past to qualify weapon systems in EMR and EMP environments. It can also be used to evaluate prototype design behavior in these environments, as well as for research. Recently, an experiment was conducted in which a direct-drive waveform was induced by electromagnetic fields in the working volume and injected into test components to monitor susceptibility.

The EMR and EMP sources and data instrumentation are housed in the control room. Only one source can be connected at a time through a transition feed to the working volume. The working volume is essentially a truncated, tri-plate, rectangular coaxial transmission line that terminates into a 50-Ohm load. It has a 50-Ohm intrinsic impedance defined by

$$Z_o = \frac{377}{4[w/d + 2/\pi(1 + \coth(\pi g/d))]} = 50\ \Omega \qquad (1)$$

where w = 11.3 m, the width of center conductor, d= 8 m, the separation of ground planes, and g = 4.25 m, the separation between the edge of the center conductor and side walls.

Ideally, the longest wavelength, or the cutoff wavelength, at which EMES can support fundamental TEM propagation without higher order modes is approximately

$$\lambda_c = 2d = 16\ m \qquad (2)$$

where λ_c is the cutoff wavelength and d is the same as above. This corresponds to a cutoff frequency, above which higher order modes can exist, of

$$f_c = \frac{c}{\lambda_c} = 19\ MHz \qquad (3)$$

where c = $3*10^8$ m/s, the speed of light. Radio frequency (RF) absorber is used to suppress higher-order modes above the cutoff frequency to preserve the uniform, planar nature of the EM propagation in the working volume. The maximum absorber length needs to be ¼ of the cutoff wavelength, λ_c; therefore, the absorbers are each 4 m long [2].

Table 2. Performance Characteristics of the Electromagnetic Environments Simulator

TEM Cell	24 m (L)
Working-volume dimensions	4 x 11 x 5 m (HxWxL)
E-field polarization	Vertical
Electric Field intensity (max)	
CW (0.100 – 250 MHz)	125 V/m @ 4 m
Pulsed	300 kV/m @ 4 m

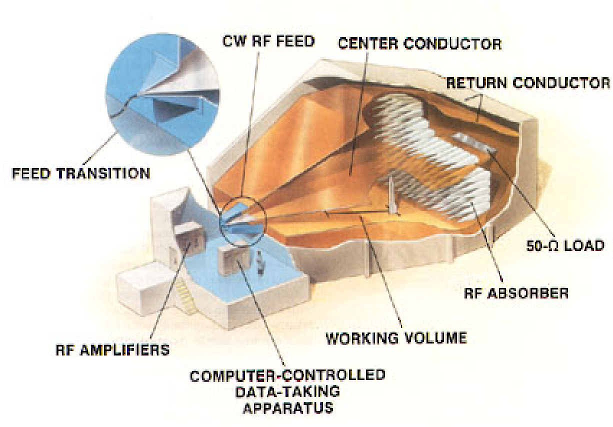

Figure 5. The Electromagnetic Environments Simulator

A. Electromagnetic Environments Simulator Upgrades

The same absorbers have been in the facility since its inception over twenty five years ago, and they are becoming fragile. Recently, about one third of the 300 absorbers were replaced, and a non-metallic support structure was constructed. The EMP source was recently refurbished and operated after a long period of non-use. It is planned to incorporate a new 5 kW amplifier for EMR testing with a frequency range of 100 kHz to 250 MHz. The new amplifier requires a larger feed to the transition section that connects to the working volume and also a new 50-Ohm load that can handle the 5 kW source. The new feed and load are scheduled to be incorporated very soon.

B. Electromagnetic Environments Simulator Diagnostic Capabilities

As part of the recent upgrades, the data acquisition system was modernized to include three Tektronix 694 oscilloscopes with bandwidths of up to 3 GHz per channel and a custom Labview program to retrieve data. Two scopes are dedicated to the source diagnostics, and one scope is dedicated for customer use. Electric and magnetic fields in the working volume can be measured with either ground-plane or free-field D-dot or H-dot sensors, respectively. The signals from the ground-plane sensors can be routed to the screen room in the control room through coaxial cables under the floor of the working volume. Routing the signals in this manner prevents electromagnetic interference from the test fields; however, the signal attenuation at high frequencies due to the long cable length must be convolved out of the test data. Free-field probes and other diagnostics in the working volume can be routed through the fiber-optic systems discussed above.

IV. THE ANECHOIC CHAMBER

Anechoic chambers are metallic rooms lined with absorbers which suppress nonuniform fields and standing waves. Sandia's Anechoic Chamber is large (10 m L X 7 m W X 5 m H). It supports frequencies of 500 MHz and above, with the lower frequency limit due to the absorbers used in the chamber. The Anechoic Chamber can be used for a variety of CW or pulsed EMR testing, and its performance characteristics are listed in Table 3 and a picture is shown in Figure 6.

The EMR sources and diagnostics are similar to those of the Mode-Stirred Chamber which are discussed in the next section. The Anechoic Chamber is a good complement to the Mode-Stirred Chamber. The Anechoic Chamber supports uniform plane waves, whereas the Mode-Stirred Chamber intentionally randomizes fields. The Mode-Stirred Chamber effectively bathes an entire test object in electromagnetic fields, effectively finding all points of electromagnetic leakage. However, antenna gain values are averaged out. In the Anechoic Chamber, an entire test object cannot be illuminated all at once due to the planar propagation of the fields; however, antenna gain values can be determined.

Table 3. Performance Characteristics of the Anechoic Chamber

Dimension	5 x 7 x 10 m (HxWxL)
Turntable diameter	2 m
Low-frequency limit	500 MHz
Absorber height	0.9 m
Input power – CW/ Pulsed TWTs	1 kW, 0. 500 – 18 GHz
	40 W, 18 – 40 GHz

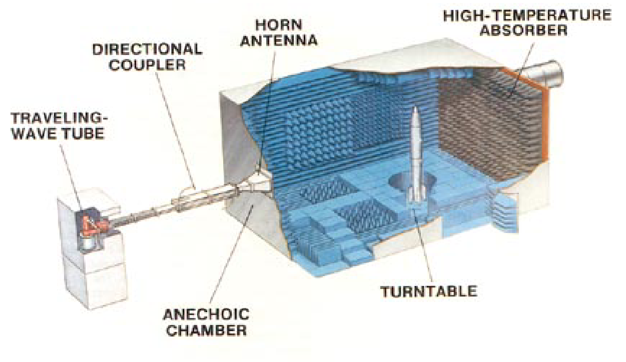

Figure 6. The Anechoic Chamber.

V. MODE-STIRRED CHAMBER

The Mode-Stirred Chamber at SNL is a large (11 m L X 7 m W X 4 m H) welded aluminum room where losses have been minimized in order to maximize the chamber's electromagnetic reverberant nature. The chamber sources are solid-state and traveling-wave tube (TWT) amplifiers that supply up to 1 kW from 220 MHz to 18 GHz, and 40 W from 18 – 40 GHz. The fields produced inside the chamber are pseudo-randomly directional and non-planar in nature and are introduced into the chamber via a horn and mixed by a paddle rotating at 30 rpm (1 revolution every 2 seconds). Amplitude is controlled by feedback signals from field monitors located on the chamber walls. The performance characteristics of the Mode-Stirred Chamber are listed in Table 4, and a picture is shown in Figure 7.

Table 4. Performance Characteristics of the Mode-Stirred Chamber

Dimension	4 x 7 x 11 m (HxWxL)
Design	Welded Aluminum
Entrance Dimensions	3.7 x 3.7 m
Frequency	0.22 – 40 GHz
Input power – CW Solid State and TWT amplifiers	1000 W, 0.220 – 18 GHz
	40 W, 18 – 40 GHz
Peak Field Strength	~3000 V/m, 0.22 – 18 GHz
	~600 V/m, 18 – 40 GHz

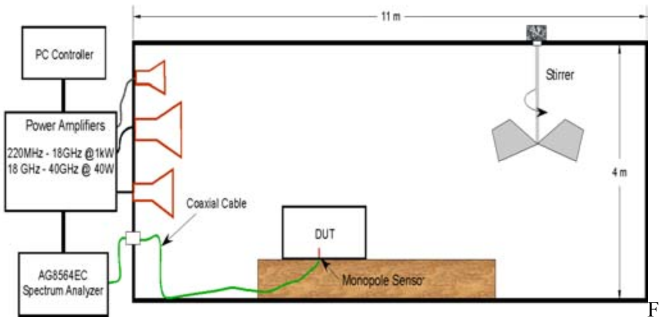

Figure 7. The Mode-Stirred Chamber.

A. Mode-Stirred Chamber Upgrades

A new suite of amplifiers has recently been installed to replace a system that was twenty years old. The new amplifiers also expand our previous capabilities of 200 W to 1 kW from 220 MHz to 18 GHz, and added the ability to test from 18 GHz to 40 GHz.

B. Mode-Stirred Chamber Diagnostics

Field measurements from 220 MHz to 18 GHz are made using short (4.33 mm), non-perturbing monopole probes. These probes are fabricated out of APC-3.5 precision connectors as shown in Figure 8. The outer conductor of the connector body is machined down to its reference plane, and a center pin that is 4.33 mm above the ground plane (the chamber wall) is inserted into the connector.

.Figure 8. 0.22 – 18 GHz 4.33 mm Monopole Probe.

The following equations describe the calculation of the normal electric field, E_n, from the probe output power measurement. From the equivalent circuit of the probe in Figure 9, the voltage across the load, V_L, is given by the following equation:

$$V_L = h_{eff} E_n \frac{Z_L}{Z_a + Z_L} \qquad (4)$$

where V_L = the load voltage, h_{eff} = the sensor effective height (m), E_n = the normal electric field, Z_L = the input impedance of power meter (50Ω), and Z_a= the monopole input impedance (Ω). The power delivered to Z_L is measured and the load voltage across the load is

$$V_L = \sqrt{P_L Z_L} \qquad (5)$$

where P_L = the sensor output power (W). Combining and rearranging Equations (4) and (5), the normal electric field is

$$E_n = \sqrt{\frac{P_L}{Z_L}} \frac{Z_a + Z_L}{h_{eff}} \qquad (6)$$

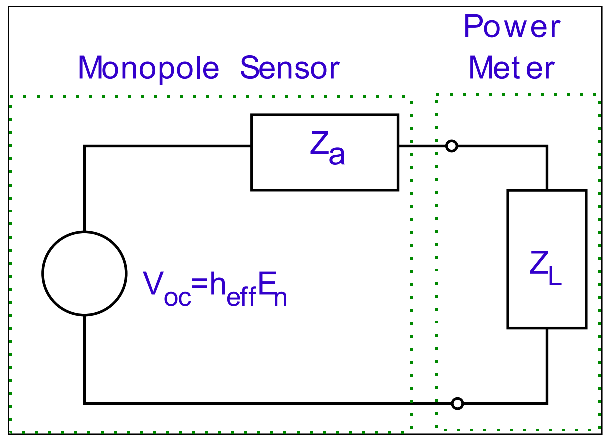

Figure 9. Monopole Equivalent Circuit.

To make measurements from 18 to 40 GHz, a "zero-length" monopole probe is used, which is a modified 40 GHz k-connector, as shown in Figure 10 [3]. This high frequency probe is non-resonant and capable of measuring the electric field on the walls of the Mode-Stirred Chamber up to 40 GHz. The outer conductor of the connector body was machined down to be flush with the center pin. A male pin was inserted into the female acceptor pin to better match the computational model. Hence the term "zero length" because the monopole does not protrude above the ground plane.

Figure 10. "Zero-length" 18 – 40 GHz Monopole Probe.

VI. ELECTROMAGNETIC ANALYSIS AND MODELING CAPABILITIES

Sandia actively develops and utilizes high fidelity analytical, computational, and modeling tools in the areas of electromagnetics and plasma physics. One key use is component and system response, which includes susceptibility, vulnerability, and hardening, in electromagnetic environments. Other uses include design and performance analyses of high-voltage components, high-frequency microelectronics, antennas, and photonic components. The suite of computational tools includes time-domain and frequency-domain codes, can accommodate three-dimensional models, and runs on large parallel computing platforms.

The combined resources of experimental and analytical capabilities are highly beneficial. Either can be used alone or in conjunction to validate codes and models with canonical experiments or to define test configurations and parameters with analysis.

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REFERENCES

[1] G. H. Schnetzer, R. J. Fisher, and M .A. Dinallo, "Measured Response of Internal Enclosures and Cables Due to Burnthrough Penetration of Weapon Cases by Lighting", SAND94-0312, Sandia National Laboratories, August 1994..

[2] N. Pollard, "A Broadband Electromagnetic Environments Simulator (EMES), Sandia National Laboratories.

[3] H.G. Hudson, L.K. Warne, S.L. Stronach, M. Morris, T. Lehman, and K. Lee, *Statistical Characterization of the Sandia National Laboratories Mode-Stirred Chamber,* Facility Test Report, December 1998.