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First edition
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BASIC EMC PUBLICATION

Electromagnetic compatibility (EMC) –

Part 4-32:
Testing and measurement techniques –
High-altitude electromagnetic pulse (HEMP) simulator compendium

Compatibilité électromagnétique (CEM) –

Partie 4-32:
Techniques d'essai et de mesure –
Compendium des simulateurs d'impulsions électromagnétiques à haute altitude (IEMN-HA)

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FOREWORD

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Technical reports do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful by the maintenance team.

IEC 61000-4-32, which is a technical report, has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility (EMC). It has the status of a basic EMC publication in accordance with IEC Guide 107.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
77C/116/CDV	77C/126/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until 2005. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 4-32: Testing and measurement techniques – High-altitude electromagnetic pulse (HEMP) simulator compendium

1 Scope

This Technical Report provides information about extant system-level high-altitude EMP (HEMP) simulators and their applicability as test facilities and validation tools for immunity test requirements. This report provides the first detailed listing of HEMP simulators throughout the worldand is the preliminary summary of this effort. It should be updated on a regular basis as the status of test facilities change.

The main body of the report is a collection of datasheets describing 42 EMP simulators in 14 countries that are still operational or could be made available for use by the international community.

The owners of the simulators have provided the information contained in this report. The IEC shall not be held responsible for the accuracy of the information.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61000-2-9: *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 9: Description of HEMP environment – Radiated disturbance.* Basic EMC publication

IEC 61000-2-10: *Electromagnetic compatibility (EMC) – Part 2-10: Environment Description of HEMP environment – Conducted disturbance*

3 General

A high–altitude (above 30 km) nuclear burst produces 3 types of electromagnetic pulses that are observed on the earth's surface:

- early-time HEMP (fast);
- intermediate-time HEMP (medium);
- late-time HEMP (slow).

Historically most interest has been focused on the early-time HEMP that was previously referred to as simply "HEMP". Here we will use the term high-altitude EMP or HEMP to include all 3 types of waveforms. The term NEMP[1] covers many categories of nuclear EMPs including those produced by surface bursts (SREMP)[2] or created on space systems (SGEMP)[3] .

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[1] Nuclear Electromagnetic Pulse

[2] Source Region EMP

[3] System Generated EMP

The classification of the HEMP environment used in this report is the radiated electromagnetic environment (incident plus ground reflection, if any) that would be experienced by the external surfaces of a system thereby producing voltages and currents prevailing at typical locations within a system or installation through external and internal coupling processes. This approach is appropriate because the HEMP environment is generated in the upper atmosphere and is initially described as an external electromagnetic environment (both radiated and conducted; see IEC 61000-2-9 and IEC 61000-2-10). For components, devices, equipment, subsystems or systems located within an installation, the conducted and radiated environments incident at their locations are determined by the amount of protection provided by EM shields and/or conductive point of entry (PoE) elements present in the installation or enclosure. System-level EMP simulators are the most effective means of assessing the effectiveness of these protection measures.

4 Terms and definitions

4.1
conductive point-of-entry
penetrating conductor, electrical wire, cable or other conductive object, such as a metal rod, which passes through an electromagnetic barrier

4.2
electromagnetic barrier
topologically closed surface made to limit EM fields and conducted transients from entering the enclosed space. The barrier consists of the shield surface and points-of-entry treatments, and encloses the protected volume

4.3
electromagnetic pulse (EMP)
nuclear electromagnetic pulse (NEMP)
all types of electromagnetic fields produced by a nuclear explosion. Also referred to as nuclear electromagnetic pulse (NEMP)

4.4
electromagnetic shield
electrically continuous housing for a facility, area, or component used to attenuate incident electric and magnetic fields by both absorption and reflection

4.5
HEMP
high-altitude nuclear EMP

4.6
high-altitude (nuclear explosion)
height of burst above 30 km altitude

4.7
point-of-entry (PoE)
physical location (point) on an electromagnetic barrier, where EM energy may enter or exit a topological volume, unless an adequate PoE protective device is provided. A PoE is not limited to a geometrical point. PoEs are classified as aperture PoEs or conductive PoEs according to the type of penetration. They are also classified as architectural, mechanical, structural or electrical PoEs according to the functions they serve

4.8
shielding effectiveness
measure of the reduction or attenuation in the electromagnetic field strength at a point in space caused by the insertion of a shield between the source and that point; usually expressed in decibels (dB)

5 Datasheet definitions and instructions

The request for information that was sent to owners of worldwide EMP simulators included the following definitions and instructions for supplying the requested information.

5.1 General information

Simulator type:	Specify the type simulator using one of Baum's 3 categories: guided-wave, dipole, or hybrid.
Termination or resistive loading:	For guided-wave simulators, specify the type termination used (for example, output conic section with approximate point resistive load, output conic section with distributed resistive load, no output conic section with sparse, distributed resistive load). For dipole simulators, specify whether antenna is resistively loaded. For hybrid simulators, specify whether the antenna is uniformly resistively loaded or end-terminated.
Major simulator dimension(s):	Specify the longest dimension of the simulator in meters (for example, 80 m long).
Test volume dimensions:	Specify the dimensions in meters of the usable test volume (for example, 15 m (high) by 20 m (wide) by 50 m (long)). Specify each if more than one test volume is available.

5.2 Simulator input options

Primary pulse power:	Describe the type generator and peak output voltage of the primary high-voltage pulse generator used (for example, 6-MV Marx generator with peaking capacitor).
Repetition rate:	Specify the usable pulse repetition rate and any limits on how long the simulator can be operated at this rate (for example, 12 pulses per hour) for the primary pulse power source.
Low-voltage or CW test capability:	Specify any lower-voltage input sources available (for example, 50-kV, 2-ns rise time, 50-pps pulse generator) and any continuous wave (CW) sources available (for example, 10-kHz to 1-GHz CW generator).

5.3 Electromagnetic field characteristics (in test volume unless otherwise noted)

Electric field polarization:	Specify the electric field orientation with respect to the earth (for example, vertical).
Line impedance:	For guided-wave simulator, specify the transmission line impedance (for example, 120 Ω). For dipole and hybrid simulators, specify the cone or bicone impedance of the early-time radiating element (for example, 150 Ω).
Wave impedance:	Specify the impedance of the field in the test volume (for example, 377 Ω – HEMP spherical wave).
Peak electric field:	Specify the range of peak electric fields available in the test volume (for example, 20 kV/m to 100 kV/m).
Peak magnetic field:	Specify the range of peak magnetic fields available in the test volume (for example, 50 A/m to 250 A/m).

Pulse rise time: Specify the 10 % to 90 % pulse rise time (for example, 9 ns).

Prepulse: Specify the maximum value of the prepulse as a percentage of the peak output of the simulator (for example, 10 %).

Pulse width: Specify the 1/e or full-width, half-maximum pulse width (e.g., 580 ns (1/e) or 400 ns FWHM).

Field uniformity: Guided-wave simulators – Use the following qualitative ratings to specify the worst-case uniformity of the peak value of the principal field component in the test volume:

Excellent – better than ±10 %

Good – between ±20 % and ±10 %

Fair – between ±50 % and ±20 %

Poor – worse than ±50 %

Use the plane in the test volume closest to the simulator input and normal to the direction of propagation of the wave. Specify the fall-off (1/r) of the peak field in per cent from the front to the back of the test volume. Specify the maximum value of any non-principal component in per cent of the peak value of the principal component. Example:

Excellent uniformity of peak value of vertical field component.

20 % fall-off of peak field from front to back of test volume.

Horizontal field components ≤15 % of vertical component everywhere in test volume.

Other simulators – Specify the maximum and minimum values of the peak of the principal field component anywhere in the test volume (for example, horizontal E-field parallel to simulator axis 65 kV/m maximum and 10 kV/m minimum). Specify the maximum value in per cent of the peak value of the principal component of any non-principal component (for example, vertical and other horizontal components ≤ 25 % of principal horizontal component).

Other: Describe any other pertinent technical features of the simulator not covered above.

5.4 Administrative information

Location: Specify the location of the simulator (nearest city or military base and country).

Owner: Specify the name of the company or agency that owns the simulator.

Point of contact: Specify the name and full address of the person to contact for more information about the simulator.

Initial operation date: Specify the year in which the simulator first became operational.

Status: Specify the current status of the simulator (for example, under development, operational, stand-by, inoperative).

5.5 Availability

Government users:	State availability of simulator for use by government agencies and any restrictions on this availability (for example, available to government agencies of any EU country).
Industry users:	State availability of simulator for use by private companies and any restrictions on this availability (for example, available to any private company with endorsement of government agency of any EU country).

5.6 Other technical information

Photograph:	Provide one or more high-quality colour photographs of the facility that will provide readers of the compendium with a basic understanding of the size and scope of the simulator.
Typical time-domain waveform:	Provide a representative sample of a time-domain E-field or B-field measurement from the simulator test volume.
Typical frequency-domain spectrum:	Provide a Fourier transform of a representative pulse from the simulator test volume.
General description:	Provide whatever general historical and descriptive information about the facility that you would like to present and can fit in the available space.
Available instrumentation:	Describe the sensors and data acquisition equipment available for use with the EMP simulator. Include information about the frequency ranges and/or rise times of the instrumentation.
Auxiliary test equipment:	Describe any auxiliary test equipment, such as direct drive (pulse or CW) equipment, associated with the EMP simulator.

6 Project description

6.1 Introduction

This report reviews worldwide EMP simulators in terms of their characteristics, capabilities, and limitations. This historical section of the report is a summary and update of papers presented at international conferences in 1984, 1995, 1998, and 1999 and describes several EMP simulators that have been built and dismantled as well as those that currently exist [1-4]. The section that follows is organised into 42 datasheets for individual EMP simulators that remain in operation or could be put back into operation for EMP testing. Other simulators exist in China, Poland, and probably elsewhere, but it was not possible to obtain information about them in time for this report.

Dr. Carl Baum (U.S. Air Force, Kirtland AFB, New Mexico) is the father of most of the Western simulator designs through his series of Sensor and Simulation Notes. He also named many of the simulators [5]. Baum has classified non-source-region EMP simulators in 3 categories: guided-wave, dipole, and hybrid [6], [7]. The scope of the report is restricted to those simulators designed to simulate the nuclear EMP outside of the source region and in particular those that simulate the electromagnetic environment caused by a high-altitude nuclear explosion (HEMP).

The end of the Cold War has provided the opportunity to learn of electromagnetic pulse (EMP) simulators developed in the former Soviet Union as well as China and to compare their performance characteristics and test methods employed in them to those of western simulators. While similarities exist with EMP simulators developed in the U.S. and other western countries, in some cases the simulators developed by researchers of the former Soviet Union and other Warsaw Pact nations provide some very interesting differences in approach.

No one perfect EMP simulator exists. This report describes several examples that fall into Baum's 3 categories (guided-wave, dipole, and hybrid) of HEMP simulators. All designs have inherent limitations; hence the large variety of designs that exists. Some analysis and extrapolation of results must always be done. The ideal of a simple "zap" test to prove a system hard to EMP is just that – an unachievable ideal.

6.2 Guided-wave simulators

Guided-wave simulators use metal "plates"[4] driven by one or more high-voltage generators to propagate a nominally TEM wave through a region frequently called the "working volume." The test object is located in this working volume. This class of simulator is used primarily to simulate the free-space environment produced by a high-altitude nuclear burst. Most existing guided-wave simulators produce a vertical electric field (and horizontal magnetic field) because in this case the earth can be used as one of the conducting plates.

This most ubiquitous of EMP simulators is highly efficient in its use of pulsed power. For example, a 1-MV Marx generator can provide high-fidelity fields with strengths of >100 kV/m over objects as long as 6 m. These fields usually have the "double-exponential" shape characteristic of a high-altitude EMP. Guided-wave structures can propagate pulses with sub-nanosecond rise times if the generator is capable of producing them. Simulator impedances and field distributions can be calculated readily, and the fields can be made uniform over a large volume of space.

4 The term "plates" is commonly used; however, in almost all EMP simulators the conductors for the transmission line are formed of parallel wires or wire mesh.

Guided-wave simulators are the best choice for testing missiles and aircraft in simulated in-flight configurations. For good simulation fidelity, the test object dimensions should not exceed 60 % of the plate spacing. While they often are used to test ground vehicles (for example, jeeps, tanks, trains), this is not a high-fidelity simulation because it does not provide the ground reflection needed for assessing the EMP coupling characteristics of systems situated on the earth's surface. In general, guided-wave simulators are not transportable; the test object usually must be brought to the simulator.

Several guided-wave simulators outside the U.S., particularly those in the former Soviet Union, have generators that produce very long pulses (microseconds to milliseconds) to provide some information on system response to an endo-atmospheric nuclear burst albeit absent the ionizing radiation and associated conductivity that would exist in a true SREMP environment.

Guided-wave simulators come in two basic types: those with symmetrically tapered input and output-feed sections usually attached to a parallel plate section (Table 1) and those with a single-feed section attached to a sparse, distributed, resistive load, usually without an intervening parallel-plate section (Table 2).

The AFWL-Los Alamos EMP Calibration and Simulation (ALECS), located in the U.S., is one of the earliest examples of the symmetric type guided-wave simulator and is typical of this genre. Built in the early 1960s, it has been used for numerous tests including missiles, scale models of aircraft, communications systems, and automobiles. The facility is used in both pulse and continuous wave (CW) modes. In pulse mode a Marx generator provides input voltage of up to 2 MV. Test data is recorded in a RF-shielded room located beneath the transmission line. The Advanced Research EMP Simulator (ARES) was built in the late 1960s to overcome the size restrictions of ALECS. The largest EMP simulator in the world is the Trestle. The structure was built to perform tests of aircraft in the in-flight mode with horizontally polarized waves. The structure can accommodate 747-size aircraft. The wooden platform on which the aircraft sits is 36 m above the earth and with its ramp over 180 m long. More than 6,5 million board feet of lumber were used in the construction, and more than 100,000 special wooden bolts hold it all together.

Two very large guided-wave simulator complexes are operated by the Ministry of Defence in Russia: one at the Central Institute of Physics and Technology (CIPT) at Sergiev Posad near Moscow and one at the Science Research Centre near St. Petersburg [8-11]. Each of the Russian complexes includes two large guided-wave simulators driven by a centrally located pulse generator. The very large cylindrical housing for the multi-megavolt air-insulated Marx generator adjacent to another large dielectric structure housing the pulse shaping circuitry (e.g., “peaking capacitor”) are distinguishing characteristics of these facilities.

In the case of the St. Petersburg complex, one of the simulators is used for high-altitude EMP environments and one for source-region EMP environments. This complex specializes in evaluating the effects of EMP on buried structures. These simulators include a capability for testing objects either on, or buried beneath, the earth’s surface. In SEMP-12-3 an underground transmission line, which consists of 2 rows of vertical electrodes positioned at a relative distance of 50 m, is connected to the transition sections leading to the pulse generator section and the matched restive load.

The SEMP-6 facility near Sergiev Posad is very similar in appearance to the one at St. Petersburg, but important differences exist. For example, the lower plate of the transmission line is on, not below, the earth’s surface. However, like SEMP-12-1 at St. Petersburg, the SEMP-6 provides some SREMP simulation capability by the use of large-dimension, rectangular coils in the vertical planes outside the working volume driven by pulsed current sources to produce late-time, long-duration magnetic fields in the simulator. Many different types of military systems are tested in this simulator complex. One portion of the simulator is being upgraded for 1 ns-3 ns rise-time performance.

A similar, antecedent complex that exists at the small town of Andreevka near Kharkov in Ukraine was developed and is operated by the Institute “Molniya” (lightning) [12]. As this name implies, both the Russian and Ukrainian complexes are used for studying the effects of lightning as well as EMP on systems.

Although the simulators have an output transition section, the terminations in the Russian and Ukrainian simulators do not really come to a “point”. Instead, a rectangular array of resistive elements absorbs the electromagnetic wave after it has passed through the simulator test volume.

China has a small guided-wave EMP simulator, the DM-1200, that is similar in basic geometry to the ARES system located in Albuquerque, New Mexico. However, the lower plate of the transmission line is not connected to the earth in the transition sections as in the case of ARES. The 1,2-MV Marx generator is located in a building at the end of the transmission line. The DM-1200 was developed and is operated by the Beijing Institute of Electronic Systems Engineering (BIESE) of the Ministry of Aerospace.

The "bend" in the top plate at the transition from conical to parallel geometry in traditional guided-wave EMP simulators produces reflections that limit the unperturbed fields to the forward portion of the parallel plate section in this type simulator [13]. This bend and its twin at the output transition also produce higher-order mode effects particularly limiting the usefulness of these simulators in continuous-wave (CW) mode.

SIEM-2, built in France in the late 1970s for testing strategic missiles, was the first of a class of simpler geometry guided-wave simulators with improved high-frequency performance over the more traditional symmetrical geometry (Table 2) [14]. These simulators basically use just the input conic section in the traditional-geometry simulators. This configuration sometimes is referred to as a “horn” simulator. The large, but sparse, distributed resistive termination used in these simulators allows the high-frequency components of the pulse to radiate out the end of the simulator rather than being trapped as standing waves in the transmission line. Simulators with this basic geometry exist in Germany, Sweden, Switzerland, Italy, Israel, and reportedly Poland (so far, it has not been possible to obtain any information on the Polish simulator).

The conical geometry of the input section that transitions from the relatively small dimensions where the wave is launched to the large dimensions of the working volume produces a spherical wave rather than the desired plane wave. This causes different parts of the test object to experience the arrival of the wave at somewhat different times and introduces non-vertical components to the electric field. In traditional simulator designs, designers controlled this problem by keeping the transition angle small (typically 15°), which makes the simulator dimensions large.

A different approach has been taken in a new simulator built by France Telecom/CNET in Lannion, France [15-17]. In this simulator, the electromagnetic wave passes through a large lens made from plywood. The effect of the lens is to refract and slow down the electromagnetic waves while traversing the dielectric material. In this way, the spherical wave is transformed into a planar one, because the shape of the lens slows down waves travelling along the direction of the simulator axis more than waves diverging from the simulator axis. The developers claim very good field characteristics (for example, homogeneity, rise time, planarity) in the simulator working volume beyond the lens.

The indoor ERU-2M simulator at Sergiev Posad, Russia is significantly different from those described above because it employs a 3-plate transmission line. The 1-MV pulse generator is much more compact than those typically found in the simulators of the former Soviet Union and produces a 2 ns rise-time field in the simulator working volume.

In addition to those listed in Tables 1 and 2, guided-wave simulators exist or formerly existed in Poland and the former East Germany. Egypt reportedly is developing a small guided-wave simulator.