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EMP: A Brief Tutorial

George H Baker, III, *James Madison University*

The Nuclear Electromagnetic Pulse (EMP): Brief Tutorial

G. H. Baker
Professor
James Madison University

Background. Since the nuclear weapon atmospheric test days of the 1950s, it has been known that a single nuclear weapon detonated at high altitudes can disrupt the electronic systems on the ground at large distances from the burst. A nuclear detonation at altitudes from about 30 to 500 kilometers generates a strong electromagnetic pulse (EMP) that propagates to points on the ground within the line-of-sight of the burst. For bursts above 100 kilometers, electronics can be affected over continental scale areas. For example, a one-megaton burst produces high EMP levels out to a horizon range of about 1000 km. Thus one burst would expose all of Western Europe. The EMP induces large voltages and currents in antennas and cables of electronic systems that will upset operation or damage circuit components if protection measures are not present.

EMP Environments. EMP arises from two principal sources, the first of which is the gamma rays emitted by the nuclear detonation. Gamma rays represent about 1/1000th of the total bomb energy and are emitted within ten billionths of a second. The amount of gamma emitted by a one- megaton detonation is about 4×10^{12} Joules. The gamma rays, by a process known as the "Compton Effect," strip electrons from air molecules to create a large-scale electron current in the upper atmosphere. This electron current is deflected by the earth's magnetic field and thereby radiates an intense electromagnetic pulse (EMP) over extensive portions of the earth's surface (Figure 1). Effects extend to ground areas within the line-of-sight of the burst (Figure 2).[i]

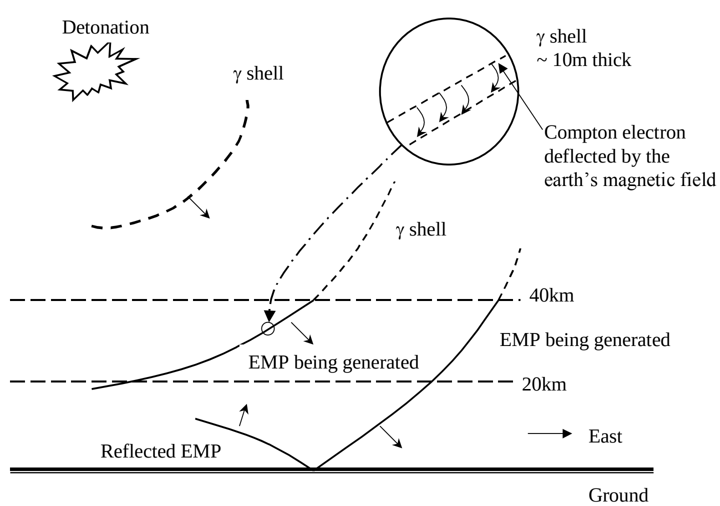


Figure 1. Mechanism of gamma-induced EMP from a high-altitude burst

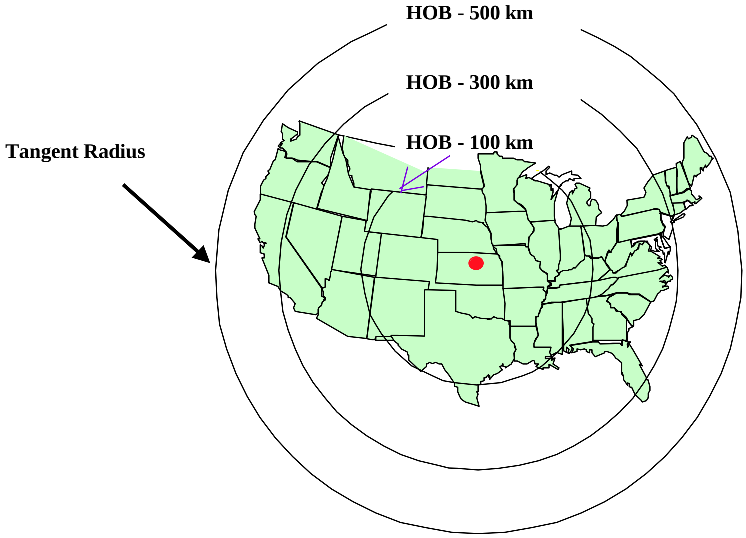
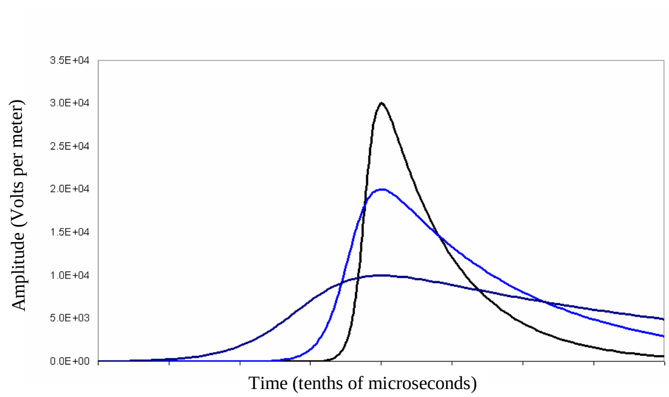


Figure 2. Single burst simultaneously affects systems over large geographic areas.

The electric field behavior in time has the approximate characteristics graphed in figure 3. The graph shows three typical waveforms. The shape varies with angle to the burst of the observer position and with the gamma output characteristics. Pulses of larger amplitude tend to be shorter in duration.



$$E(t) = \left(1 + \frac{\alpha}{\beta}\right) \frac{Ae^{\alpha t}}{1 + \frac{\alpha}{\beta} e^{(\alpha+\beta)t}}$$

where A = peak amplitude

α = rise rate

β = decay rate

Typical values are $A = 3 \times 10^4 V/m$; $\alpha = 10^8 \sec^{-1}$; *and* $\beta = 10^7 \sec^{-1}$

Figure 3. Waveform of the gamma-induced EMP

Geo-locations closest to the burst have faster rise times on and higher peak amplitude on average. Geo-locations closer to the horizon have slower rise times and higher peak amplitude. The duration of the pulse is governed by the behavior of the Compton electrons rather than the weapon gamma output.

The second significant type of EMP from high altitude bursts is a low frequency, low amplitude field caused by explosion plasma motion in the upper atmosphere. This environment is commonly referred to as magnetohydrodynamic EMP or MHD EMP. The plasma created by the explosion perturbs the earth's magnetic field which, in turn, generates electric fields on the Earth's surface and the upper layers of the ground. MHD EMP effects are similar to electrical disturbances caused by solar storms. MHD EMP generation physics are complicated and subject to large uncertainties. Probably the best example of MHD EMP fields is a measurement of the magnetic intensity underneath the 1962 "Starfish" nuclear weapon test at Johnston Island shown in Figure 4. The trace was measured just below the 1 megaton, 400 km high detonation.

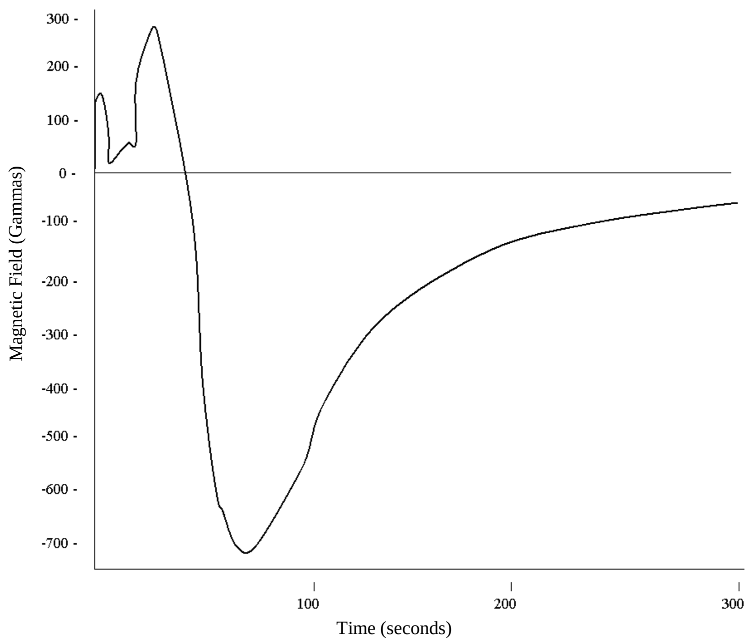


Figure 4. Magnetometer data from the Starfish nuclear test (1 Gamma = 10^{-5} Gauss)

EMP Coupling to Systems. The gamma-induced EMP contains strong frequency components up to about 100 megahertz. Wires and antennas of lengths greater than ~ 1 meter will couple signals of amplitudes ranging from hundreds to thousands of volts to connected equipment. Antennas or wires of length comparable to or longer than 1 meter will respond inductively in during 10 nanosecond rise time of the EMP signal. The inductance of a wire is approximately

$$L \approx 0.2 \ln\left(\frac{ct}{a}\right)$$

where c is the speed of light, t is time, and a is the radius of the antenna or wire. For a typical wire, the inductance, L, is about 10^{-6} Henrys/m.   The current driven on the wire of length h is approximated by

$$I \approx \frac{1}{L}\int E dt \approx \frac{E}{L}\frac{2h}{c}$$

if $2h/c$ is less than the pulse duration. For h = 3m, the peak current is about 300 amps. If the wire/antenna load impedance were 100 ohms, the input voltage would be 30,000 volts. The peak power coupled is I^2R or 9 million watts delivering energy of about 0.1 Joule. This energy is large enough to upset or damage typical integrated circuits. Lightning protection devices do not respond rapidly enough to arrest the fast rise- time EMP waveforms.

Elevated communication and power lines respond similarly to short wires. For long lines the peak current ranges into the thousands of amps since the EMP field sweeps along the wire traveling at near the wire signal speed, which causes an additive effect. The coupled pulse length is greater on long lines. Figure 5 graphs the current coupled to an overhead power line.

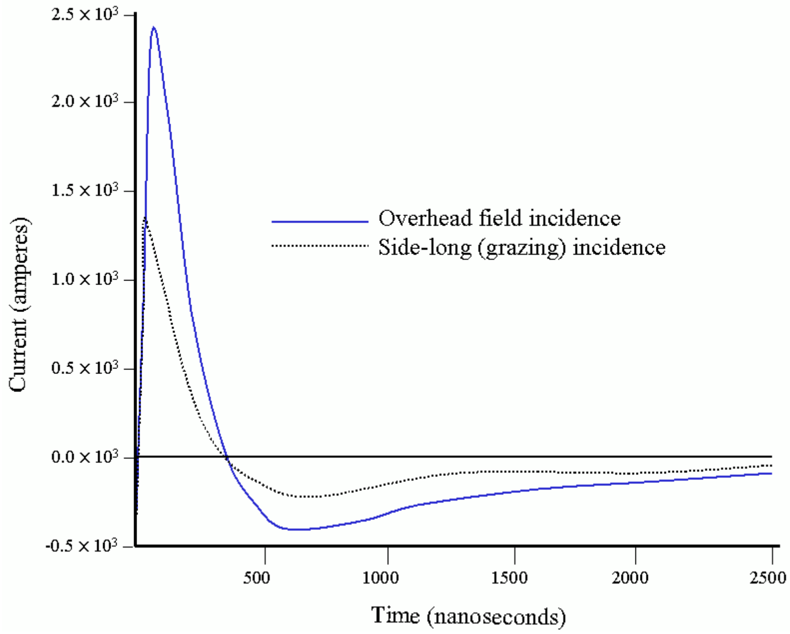


Figure 5. EMP-induced current on overhead power line

EMP Effects on Systems. EMP effects are most pronounced for long line networks (electric power, telecommunications, data networks, etc.). These are affected by both prompt and MHD EMP signals. MHD EMP does not couple significantly to short conductors including most antennas and interior system cables. Empirical evidence of EMP system effects has accrued from both U.S. and Russian atmospheric tests in the 1950s and early 1960s.

A U.S. test named "Starfish Prime" in July 1962 involved a 1.4 megaton device detonated at 400 km. The event caused street light failures in Hawaii some 1300 kilometers away.[ii] The Russians had more extensive experience than the U.S. since their high altitude nuclear shots occurred over continental land areas. Loborev has stated that they observed effects due to high altitude shots at distances of hundreds of kilometers from the detonation ground epicenter. According to Loborev, during one test, all protective devices on overhead communications lines were damaged at distances greater than 500 km. A 1000 km power line was shut down by the same event. Overvoltage-induced punctures of transmission lines, breakdown of power supplies, and communications outages were widespread during the Russian tests.[iii]

Tests of U.S. equipment in simulated EMP environments indicate that later vintage electronics are more susceptible to EMP transients due to semiconductor device miniaturation and digitalization. Test programs also show that it is difficult to predict which systems will be affected and what the operational impact of EMP effects will be for those systems that are susceptible. Some examples of effects include burnout of a portable GPS system, which exhibited power supply failures at levels as low as 5 KV/m, a regime achievable with entry-level nuclear weapons. Tests also reveal EMP vulnerabilities in commercial network telephone switches/routers, cell phone stations, and local multiplexers. Tests and analyses of the electric power transmission systems indicate the likelihood of power outages due to equipment damage and network instabilities.[iv]

System Protection. System hardening involves a combination of operational and hardware techniques. Operational techniques may include provision of spares for soft critical subsystems or boxes, or disconnecting susceptible circuits upon warning. Operational controls may also be built into software to provide circumvention and reset, error-correcting codes, voting logic, and status detection. For some non time-sensitive systems, provisions for rapid system repair may be an option.

Conceptually, hardware approaches involve the enclosing electronics within a continuous conducting shield as shown in Figure 6. Hardening techniques have been successfully demonstrated and standardized. Standard approaches rely heavily on exterior shielding and limiting the number of penetrations that have to be individually protected.[v] Such protection applied at the system exterior allows interior boxes to go untreated. This approach works well when designed in from the start. For retrofit protection, however, it is often prohibitively expensive.

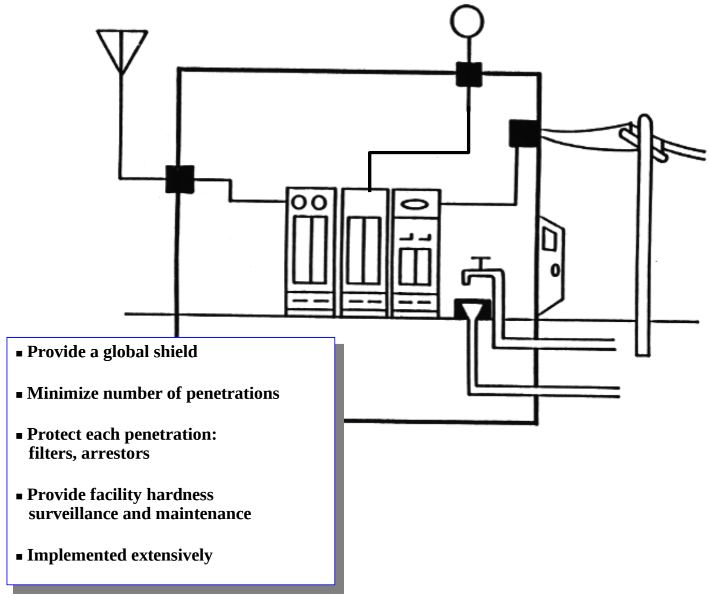


Figure 6. Low risk protection – fixed facility example

Future Directions. During the Cold War, the effects of high altitude nuclear detonations were considered by many to be ephemeral, second order effects in comparison to direct blast/thermal/radiation effects from near-surface bursts in the context of mutually-assured-destruction (or MAD) scenarios. However, as information warfare objectives have gained prominence in military operations, the likelihood high altitude nuclear scenarios have gained wider acceptance among strategic planners.[vi] When viewed in the context of infrastructure debilitation, high altitude nuclear attacks begin to make sense as a primary tactic to deny or delay an adversary's ability to respond. The use of nuclear weapons at high altitudes could prove decisive in future conflicts.

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[i] Conrad L. Longmire, On the Electromagnetic Pulse produced by Nuclear Explosions, IEEE Antennas and Propagation, Volume AP-26, Number 1, January 1978.
[ii] *Did High-Altitude EMP Cause the Hawaiian Streetlight Incident?,* Vittitoe, C.N., Sandia National Laboratories Conference Report No. SAND88-0043C, April 1989.
[iii] *Response of Long Lines to Nuclear High-Altitude Electromagnetic Pulse (HEMP)*, V.M. Loborev, IEEE Transactions on Electromagnetic Compatibility, Volume 40-Number 4, November 1998
[iv] *High Altitude Nuclear Detonations – An Overview of Infrastructure Effects*, George Ullrich, Briefing to the National Academy of Sciences, April 1999.
[v] Military EMP Standard, MIL-STD-188-125, 1990.
[vi] U.S. Congressional EMP Commission Executive Summary, 2004.

About the author: George Baker is Professor of Integrated Science and Technology at James Madison University. He also serves as Technical Director of the University's Institute for Infrastructure and Information Assurance (IIIA). He is a consultant in the areas of critical infrastructure assurance, high power electromagnetics, nuclear and directed energy weapon effects, and risk assessment. He served as senior staff on the Congressional EMP Commission. Baker is former director of the Defense Threat Reduction Agency's Springfield Research Facility, a national center for critical system vulnerability assessment. Much of his career was spent at the Defense Nuclear Agency

(DNA) as the Integrated Electromagnetics Team Leader directing system protection, underground nuclear and simulator testing and standards (MIL-STD-188-125, MIL-STD-2169B, and MIL-HDBK-423) development programs. He also headed the Agency's Innovative Concepts Division overseeing the joint US-Russian space nuclear power technology, electro-thermal chemical (ETC) gun development, radiofrequency directed energy source concept development and testing, and DNA's university grants programs. Baker received the Agency Legacy Award for his leadership and innovation. He is a member of the NDIA Homeland Security Executive Board, the Institute of Electrical and Electronic Engineers (Senior Member), the Directed Energy Professional Society (Charter Member), and the Association of Old Crows. He is a Summa Foundation EMP Fellow and holds a Ph.D. from the U.S. Air Force Institute of Technology.