Metatech

Meta-R-320

# The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid

Edward Savage
James Gilbert
William Radasky

Metatech Corporation
358 S. Fairview Ave., Suite E
Goleta, CA 93117

January 2010

Prepared for

Oak Ridge National Laboratory
Attn: Dr. Ben McConnell
1 Bethel Valley Road
P.O. Box 2008
Oak Ridge, Tennessee 37831
Subcontract 6400009137

Table 2-2. List of some types of EMP, and other related effects.

| Types of EMP and Related Effects | | |
|---|---|---|
| Acronym | Type | Description |
| EMP | electromagnetic pulse | Any electromagnetic transient signal, but typically used to refer to nuclear EMP, and often specifically early time high altitude EMP (E1 HEMP). The British used "radioflash" in the early days. |
| NEMP | nuclear EMP | As opposed to other, common EMPs, such as from lightning or ESD. |
| HEMP HAEMP | high altitude EMP | The burst is outside of the atmosphere, and the fields of interest are free field (propagating EM wave, with no induced air conductivity). |
| HABEMP | high altitude burst EMP | |
| E1 | early time HEMP | The prompt gamma part of HEMP. |
| E2 | intermediate time HEMP | The scattered gamma HEMP (E2A) and neutron gamma HEMP (E2B) |
| E2A | first part of E2 | The scattered gamma HEMP; from gammas that have scattered (secondary gammas). |
| E2B | second part of E2 | The neutron scatter gamma HEMP – from gammas created when weapon neutrons scatter from air molecules. |
| E3 | late time HEMP | Also known as MHDEMP. |
| MHDEMP | magnetohydrodynamic EMP | The late-time, low level, part of HEMP (E3), produced by the deformation of the Earth's magnetic field (blast wave, E3A), and the rise of the hot burst debris in the Earth's magnetic field (heave, E3B). |
| DEMP | dispersed EMP | E1 HEMP that propagates up through the ionosphere (which distorts the pulse into ringing oscillations). |
| SREMP | source region EMP | The region of interest is close enough to the burst that the surrounding air becomes significantly conductive. The SREMP electric and magnetic fields do not have the simple impedance relationship of free space. |

## 2.11 Energy Conservation Check

It might be that no one thinks about questioning the strength of E1 HEMP. After all, it is produced by a nuclear weapon, which everyone knows has vast energy (destructive power). However, let us look at the energy in the E1 HEMP. Remember that E1 is generated from the gammas, which typically carry away only a small fraction (typically less than 1%) of the burst's energy.

We shudder at the immense destructive power of a nuclear explosion – a full town destroyed by one weapon (of course, some of the total destruction can also come after the burst, from fires ignited by the explosion.) But with EMP there could be damage over a whole continent – can there really be so much destructive power in the E1 HEMP? The following very crude calculation verifies that the amount of energy calculated for E1 HEMP is reasonable, and is actually only a small fraction of the total energy from the nuclear burst. The significant feature about E1 HEMP is that its energy is released extremely quickly - it has very high power levels, while its energy levels are actually modest. E1 HEMP is important because of:

1. Its very high power levels, not usually seen, except in limited circumstances, such as very near lightning strikes, or very close to some very high power RF sources, such as large radars.
2. Its very large area coverage, exposed simultaneously.
3. Modern society's reliance on microscopic, high frequency, electronic devices.
4. E1 HEMP can trigger the destructive release of other energy stores (just as the flick of a match head can cause the match to ignite, which starts a wildfire, which then goes on to burn many homes).

Here we will look at energy, which is the time integral of power (E1 HEMP has very high power, but it also only lasts for a very short time).

Nuclear weapons are rated in terms of their "yield" – their explosive power, often expressed in kT or MT – kilotons or megatons. This refers to the initial energy release of the nuclear device – of all energy types, as discussed previously. As is well known, but it may be hard to comprehend, a "Ton" ("T") corresponds to the explosive power in a ton (2000 pounds) of TNT – such as the amount of explosives that a terrorist might put into a van or small truck. The largest conventional (chemical) bombs may be a few tons. The basic unit for nuclear devices is a kiloton – or what might be in a thousand terrorist vans. The Hiroshima and Nagasaki devices were reported to be about 10 to 20 kT. Thermonuclear devices can be measured in terms of megatons (a million times the yield of big conventional bombs), with the largest nuclear weapon being multiple ten's of megatons.

For this approximate check we will assume a 500 kT nuclear device. Converting to MKS units, the burst initial output energy, in Joules, is:

$$W_{500kT} = 500\ \mathrm{kT} \times 4.184 \times 10^{12}\ \mathrm{J/kT} = 2.09 \times 10^{15}\ \mathrm{J}\ .$$

In everyday units this is:

$$W_{500kT} = 2.09\times10^{15}\ \mathrm{W-s} / (60\ \mathrm{s/min}\times 60\ \mathrm{hr/min}\times 1000\ \mathrm{W/kW})$$

$$= 5.8\times10^{8}\ \mathrm{kW-hr}\quad \text{(i.e., kilowatts – hours)}$$

(using 1 Joule = 1 Watt-second). A rough estimate is that an American residence uses about 10,000 kW-hrs a year in electrical power energy, and so this 500 kT weapon represents a year's electricity need for 58,000 American homes.

E1 HEMP is produced by the gamma output of the burst. Assume a gamma efficiency of 0.1%. Then the energy into the gammas for this 500 kT weapon is:

$$W_{\gamma} = 0.001\times 2.09\times10^{15}\ \mathrm{J} = 2.09\times10^{12}\ \mathrm{J}\ .$$

Some of the gammas simply radiate out into space, away from the Earth. Figure 2-16 gives the geometry parameters for a 75 km burst height. It shows that about 0.424 of the gammas head in a direction toward the Earth's surface (for convenience of showing the angles, we drew the figure with the HOB distorted – note that the angle at the burst is actually 81.25° and the angle at the Earth's center is 8.75°). Assuming only this fraction of the gammas contribute to E1 HEMP, the energy going into E1 generation is:

$$W_{\gamma E1} = 2.09\times10^{12}\ \mathrm{J}\times 0.424 = 8.87\times10^{11}\ \mathrm{J}$$

$$= 2.46\times10^{5}\ \mathrm{kW-hr}\quad (\approx 24.6\ \text{U.S. households for a year}).$$

This is still a significant amount of energy, but remember, it is spread out over an area corresponding to much of the continental U.S.

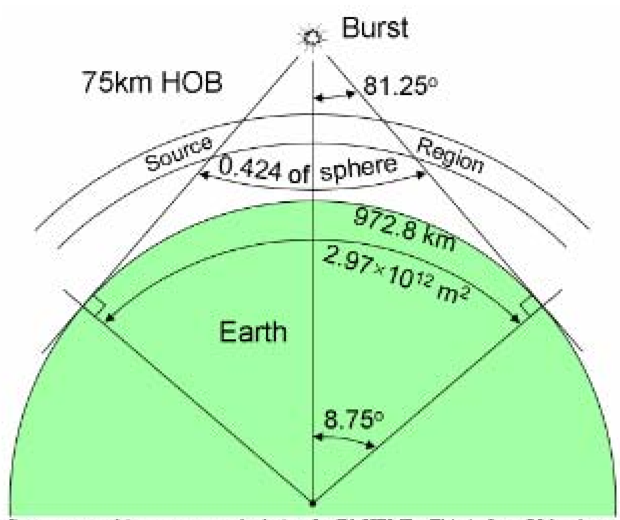



Figure 2-16. Geometry used in an energy calculation for E1 HEMP. This is for a 75 km burst height (46.6 miles, 246 thousand feet). The view shown is very distorted – the Earth is actually much larger, relative to

Now that we have the amount of weapon energy that can generate E1 HEMP, we will consider the total energy in the E1 HEMP. We will use the IEC E1 HEMP signal defined previously, which had a peak of 50,000 kV/m at the strongest point on the Earth, and energy density of 0.115 J/m². The exposed region goes out to the tangent of 972.8 km, an area of

$$A_{E1} = \pi(972.8\ \text{km})^2 = 2.973\times10^{12}\ \text{m}^2$$

(more accurately, accounting for the Earth's curvature, it is actually $2.967\text{x}10^{12}$ m²). The 50,000 kV/m is the E1 HEMP at the maximum point; it is less elsewhere, as previously shown in Figure 2-3. Averaged over the exposed region, for this case the peak is 0.1243 of the maximum (so about 6.21 kV/m). Thus, the total energy in the E1 HEMP is

$$W_{E1} = 2.967\times10^{12}\ \text{m}^2 \times 0.1145\ \text{J}/\text{m}^2 \times 0.1243^2 = 5.25\times10^9\ \text{J}$$
$$= 1457\ \text{kW}-\text{hr}$$

(approximately 53 days of electricity for a typical U.S. household). This E1 HEMP energy is only about

$$\frac{W_{E1}}{W_\gamma} = \frac{5.25\times10^9\ \text{J}}{8.87\times10^{11}\ \text{J}} = 0.59\%$$

of the energy in the gammas that generate the E1 HEMP. This is also only

$$\frac{W_{E1}}{W_{500kT}} = \frac{5.25\times10^9\ \text{J}}{2.09\times10^{15}\ \text{J}} = 0.0000025 \quad \text{(fraction, not percent)}$$

of all the energy from the burst. Thus, the E1 HEMP total energy is only a small fraction of the energy of the burst output gammas that go into generating it. The rest of the gamma energy goes into losses, such as what ultimately ends up as heating the source region, or radiating energy away from the source region (as photons: gammas, x rays, ultraviolet, infrared, etc.). Part of the lost energy was initially converted to EM energy, but ended up being lost to heat due to the air conductivity. Again, we need to emphasize that the E1 HEMP may have a small fraction of the burst's output, but it is a coherent, high level, EM pulse that is delivered very quickly. The total peak power from of the E1 HEMP is about

$$\frac{5.25\times10^9\ \text{J}}{17.25\ \text{ns}} = 3.0\times10^{17}\ \text{watts}.$$

Again, we note, this is an extremely high level partially due to the very short time duration of the pulse.

## 2.12 E1 HEMP: Instantaneous and Simultaneous

E1 HEMP has been described as instantaneously and simultaneously blanketing a continent size region. How fast is this really? We have seen that the E1 HEMP pulse is very fast – for example, the IEC waveform is 23 nanoseconds wide. And it also hits the entire exposed region essentially at once. This is because the speed of light applies – to the gammas and to the E1 HEMP signals. For a 100 km burst (62.1 miles), various time delays are:

From the burst straight down to GZ: 0.333 ms
From the burst to the farthest exposed point (tangent): 3.78 ms
From GZ out to the tangent (1122 km, or 697 miles): 3.74 ms

These can be compared to the cycle time of 16.7 ms for 60 Hz AC power. Of course, different points in the exposed region could not "know" about each other faster than the speed of light anyway, and typically cascading power failures travel at much slower speeds.

## 2.13 Observer Location Variation (Smile Diagram) and Observed Function

Often E1 HEMP is discussed in terms of the peak incident E field, as if no other characteristic matters. And most smile diagrams do plot this quantity. However, other quantities could also be of interest. In the following diagrams we show "smile" diagrams plotting different field quantities, all for the same E1 HEMP conditions (a 75 km HOB over the central U.S.). The figures are listed in Table 2-5 (the last three results listed in the table will be discussed in the next subsection). In general, the contour levels used are as fractions of the maximum incident field (which occurs at the white "+" inside the red contour in Figure 2-17).

Table 2-5. List of the sample "smile" diagrams. All cases are for the same burst scenario.

| Sample Smile Diagrams | |
|---|---|
| Smile | Display function |
| Figure 2-17 | Peak of incident E field |
| Figure 2-18 | Peak of horizontal component of incident E field |
| Figure 2-19 | Peak of north/south horizontal component of incident E field |
| Figure 2-20 | Peak of east/west horizontal component of incident E field |
| Figure 2-21 | Field direction of peak of horizontal component of incident E field |
| Figure 2-22 | Peak of vertical component of incident E field |
| Figure 2-23 | Peak of horizontal component of total E field (including reflection) |
| Figure 2-24 | Peak of vertical component of total E field (including reflection) |
| Figure 2-25 | Total energy density in incident E1 HEMP |
| Figure 2-26 | Total energy denisty in 10 to 100 MHz band for incident E1 HEMP |
| Figure 2-30 | Peak current on north/south overhead line |
| Figure 2-31 | Peak current on east/west overhead line |
| Figure 2-32 | Peak current on vertical wire |
| Parameters:<br>Burst: 40°N, 95°W, 75 km.<br>Reflected field (Figures 2-23 and 2-24): $10^{-2}$ S/m ground, observer 3 meters up.<br>Coupling (Figures 2-27 – 2-29): $10^{-3}$ S/m ground, wire 0.2 centimeters radius.<br>Horizontal: wire 100 meters long, 5 meters above ground.<br>Vertical: wire 5 meters long, base on ground. | |

The bottom edge of the source region could be defined relative to the "breakaway point". On the ray from the burst to the observer, the level of the gammas decrease along its path through the source region, and the level of the E1 HEMP increases. At some point the gammas are too weak to contribute much more to increasing the level of the E1 HEMP, nor to generated high enough air conductivity to erode away much of the E1 HEMP field. This is essentially the bottom edge of the source region. This is called the breakaway point – for points further down the ray the E1 HEMP is now a free wave, with no more effects from the sources and conductivities of the source region. This is really an arbitrary point, because the gamma effects do not suddenly stop at any point, but decrease smoothly (but sharply) with increasing air density. Often some criterion is used to define breakaway, such as the condition

$$\frac{\sigma}{d\sigma/dz} < \frac{2}{Z_o \sigma} \quad \left( \text{the right hand side is an approximation to } \frac{E}{dE/dz} \text{ in conductive air} \right)$$

where $\sigma$ is the air conductivity, E is the electric field (both vary with time), and $Z_o$ is the impedance of free space (about 376.7 ohms). (The right hand side is the attenuation distance of EM waves for $\sigma \ll \omega\varepsilon_o$.) This condition says that the conductivity is falling faster (relatively) with lower altitude than the relative fall in the E field due to conductivity. Generally we would want to take any E1 HEMP calculations to slightly lower altitudes. (Although often a simpler lower altitude criterion is used – assuming the bottom of the source region has been hit when the calculated rE product, E times distance from the burst, did not change significantly from the previous calculational position.)

The other two special positions in Figure 2-10 are related to the geomagnetic field. The "null point" is where the observer ray and geomagnetic field lines are parallel. For this point the E1 HEMP is very low (ideally it would be zero). On the opposite side of GZ is the "max field point" (or "max point" for short). This term has been used to name the location on the smile diagram where the E1 HEMP has its maximum peak level. There are two effects involved in this – one is that the most direct rays through the atmosphere generally produce the highest E1 levels, and so this would favor the GZ ray. However, the second effect is the angle at which the observer ray crosses the geomagnetic field lines – favoring the point at which they are at right angles. This point could be called the "geomagnetic max point". Note that the max field point depends on both the device and geometry, while the geomagnetic max point only depends on geometry.

For the northern hemisphere, generally the max field point is a little north of the geomagnetic max point – pulled away from the point of being at right angle to $B_{Geo}$ by the better angle through the atmosphere nearer to GZ. However, there is a third effect that also sometimes comes into play. This involves the breakaway point. For very large gamma outputs and very lower burst heights, the breakaway altitude may be pushed very low, especially for straight down rays. At such low altitudes the Compton electrons have shorter life times, thus less turning in the geomagnetic field and so less total source current to generate the E1 HEMP. Thus, for such cases (large gamma output, very low HOB), the atmosphere angle variation might not be best straight down – there it might actually be significantly suppressed. In that case the max field point might vary from the

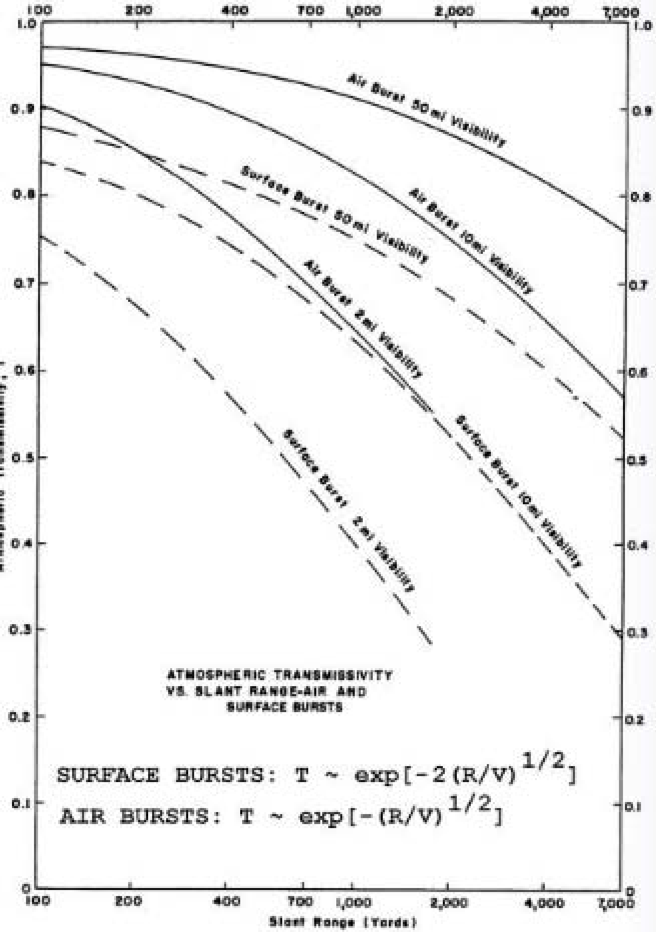
Table 2-4 summarizes some characteristics of this generic E1 HEMP signal. By construction, is has a peak of 50 kV/m. The peak power is very high, but the total energy (approximately peak power times pulse width) is modest. The pulse rises in a few nanoseconds, and has a pulse width of about 23 nanoseconds. The spectrum extends well above 100 MHz.

Table 2-4. Characteristics of the IEC E1 HEMP waveform.

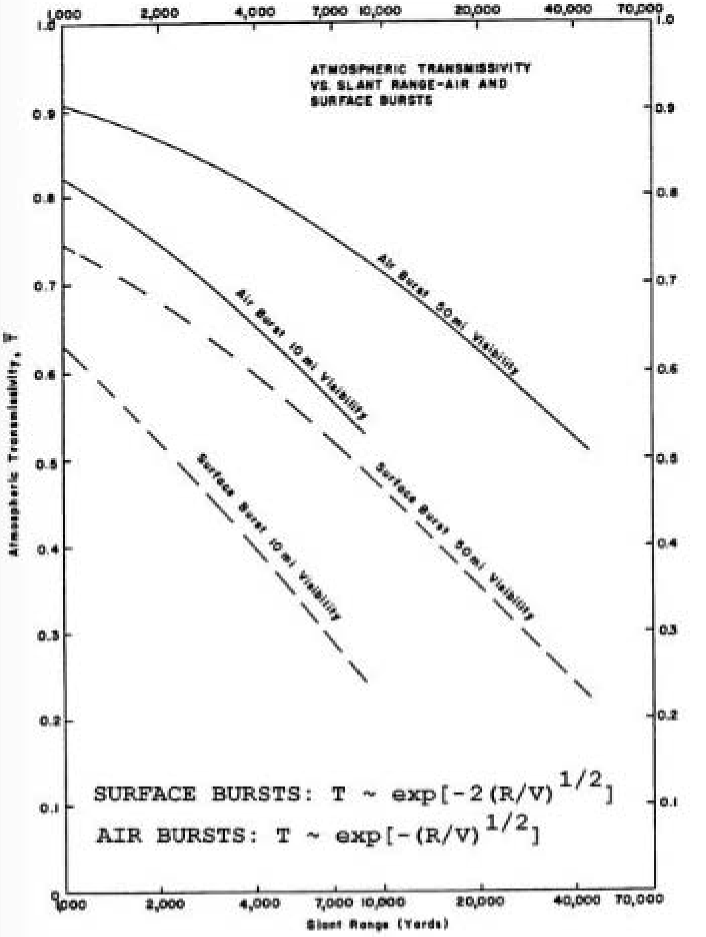
| IEC E1 HEMP Waveform Properties | |
|---|---|
| Characteristic | Value |
| Waveform peak | $E_{peak} = 50{,}000\ V/m$ |
| Spectrum peak | $E_{low\ freq} = 0.00152\ V/m/Hz$ |
| Waveform peak power | $P_{peak} = 6.64\times10^{6}\ W/m^{2}$ |
| Spectrum peak power | $P_{low\ freq} = 6.11\times10^{-9}\ W/m^{2}/Hz$ |
| Total energy | $W_{total} = 0.115\ J/m^{2}$ |
| Time of peak | $t_{peak} = 4.84\ ns$ |
| Rise time, 10% to 90% of peak | $t_{10-90} = 2.47\ ns$ |
| Pulse width, full width at half maximum | $FWHM = 23.0\ ns$ |
| Pulse width, total energy over peak power | $W_{total}/P_{peak} = 17.3\ ns$ |
| Spectrum width, total energy over peak spectrum power | $W_{total}/P_{low\ freq} = 18.8\ MHz$ |

To get a feeling for this E1 HEMP signal, consider another EM signal – a FM radio transmission at 100 MHz. Assume the transmitted power is 10,000 watts (RMS), and we are receiving the signal close by, at a distance of 1 mile (1.61 km). For a crude estimate, assume a transmitting antenna gain of $\sqrt{2}$ (2 in power). Then the peak power at the 1 mile range is 1.23 mW/m$^2$, and the peak electric field is 0.68 V/m. Thus, this signal is smaller than the E1 HEMP electric field peak by a factor of 73,500 – or a factor of $5.4\times10^{9}$ in power (97.3 dB). Figure 2-14 shows the IEC E1 HEMP waveform, compared to the FM radio signal – scaled up to the same amplitude. We can also see that the rise of the E1 pulse is similar to the rise of a cycle of the FM signal, and so we can see that the E1 HEMP does have signal content up to 100 MHz. Figure 2-15 shows the actual spectrum of the E1 HEMP waveform.

Certainly the E1 HEMP signal is much larger than the FM radio signal. However, the E1 HEMP energy density is modest - 0.114 Joules/m$^2$. By contrast, about every 3.1 minutes



Air Burst 50 mi Visibility
Air Burst 10 mi Visibility
Surface Burst 50 mi Visibility
Air Burst 2 mi Visibility
Surface Burst 10 mi Visibility
Surface Burst 2 mi Visibility
ATMOSPHERIC TRANSMISSIVITY
VS. SLANT RANGE-AIR AND
SURFACE BURSTS
SURFACE BURSTS: T ~ exp[-2(R/V)^1/2]
AIR BURSTS: T ~ exp[-(R/V)^1/2]
Slant Range (Yards)

ATMOSPHERIC TRANSMISSIVITY
VS. SLANT RANGE-AIR AND
SURFACE BURSTS
Air Burst 50 mi Visibility
Air Burst 10 mi Visibility
Surface Burst 50 mi Visibility
Surface Burst 10 mi Visibility
Atmospheric Transmissivity, T
SURFACE BURSTS: T ~ exp[-2(R/V)^1/2]
AIR BURSTS: T ~ exp[-(R/V)^1/2]
Slant Range (Yards)