A Complementary View of HEMP for Electrical Engineers

Vladimir Gurevich

Central Electric Laboratory, Israel Electric Corp., Haifa, Israel

Abstract: **Lately, the problems associated with the impact of an electromagnetic pulse of a high-altitude nuclear explosion (HEMP) on electronic and electric equipment have been debated a great deal in special technical literature. For more than a decade, dozens of government and military organizations in the US and Europe have been working intensively on this problem producing detailed bulky reports. However, so far the majority of engineers working in various civilian industries and, primarily, in the electric power industry, disregard this topic since they either are ignorant of HEMP or know it by hearsay. To change this situation, the author of this article decided to familiarize the engineers (primarily in the electrical power sector) with a contemporary view of HEMP.**

Keywords: **Electromagnetic pulse, HEMP, High-altitude Nuclear Explosion.**

I. IS THE CONTEMPORARY VIEW UP TO DATE?

It is worth noting that a contemporary view of HEMP is based on the results of the nuclear tests and researches carried out more than 50 years ago, and since then has not changed significantly. Since then, civilian standards (without any references) were taken from the old classified test reports and researches, which is the reason that there are no references. For example, all the basic data and curves given in the International Electrotechnical Commission (IEC) Standard IEC 61000-2-9 [1] are indicated in such old reports, while the Standard contains no references to them. Also, most of the further unclassified reports prepared by different organizations in 80th-90th of XX century contain a lot of images, curves, and tables taken from those old classified reports. The most modern books (such as [2]) on that subject are nothing but free interpretation and paraphrase of data taken from those later unclassified reports (e.g. [3]).

Considering the foregoing, the referenced sources may prove to be the multistage borrowings, rather than the origins of information.

II. THE BASIC PHYSICAL PROCESS

Physical processes accompanying the high-altitude explosion of the nuclear yield are very complicated and the power industry experts are not obliged to be aware of every detail. Moreover, such a detailed description of all physical processes with complex mathematical formulas may frighten the readers and cause them skip this matter. So, to avoid this, below you will find the so-called simplified HEMP theory optimized for electrical engineers, rather than for nuclear physicists.

According to the IEC classification (taken from the classified military standard)), the HEMP contains three components: E1, E2, and E3, see Fig. 1.

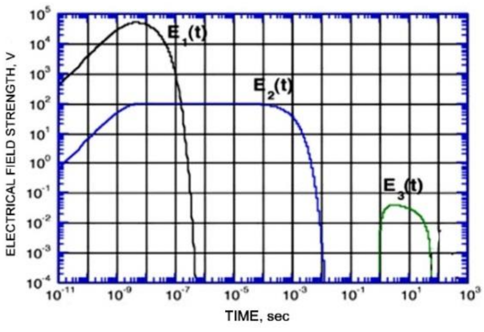

Fig 1: Parameters of HEMP components E1, E2, and E3 according to (MIL-STD-2169 and IEC 61000-2-9).

E1 is the fastest and the shortest HEMP component produced by the powerful X-radiation (γ-quanta or X-ray photons) generated upon the explosion of the nuclear yield. Upon the explosion, the X-radiation knocks out unbound electrons (the so-called Compton scattering electrons) from air atoms, see Fig. 2. Then, the electrons are captured by the Earth's magnetic field and gyrate to the Earth's surface with a speed close to the light velocity. The directed flow of electrons is the electrical current generating the magnetic field. The rapid flux of magnetic field (from 0 to the peak value) generates the high-power pulse of electric field described by Maxwell's equations. Upon the nuclear explosion, the strength of the electric field near the Earth's surface may reach 50 kV/m.

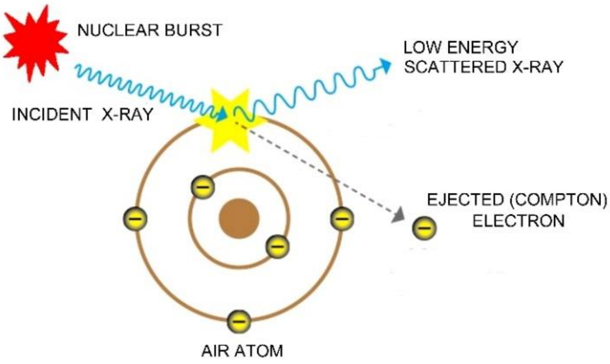

Fig 2: Emission of Compton free electrons upon the aerial nuclear explosion.

This interaction between the super velocity negative electrons and the magnetic field generates the electromagnetic wave concentrated by the Earth's magnetic field and is directed from the sky to the ground. According to IEC, the full length of a HEMP pulse may amount to 1 microsecond (1000 nanoseconds).

The E1 component is conditioned by the most intensive electromagnetic field provoking the very high overvoltages within the electric chains. Near the Earth's surface at the medium latitudes, The E1 component creates the pulse voltages up to 50 kV/m with the power density about 6.6 MW per square meter. The E1 component accounts for most of the electronic equipment failures caused by the overvoltage and breakdowns of the *p*-*n*-junction in the semiconductor elements and it internal insulation. The regular discharge arresters, optimal for the atmospheric (lightning) overvoltage protection, may be too slow to respond to the E1 component and to protect the equipment appropriately.

It should be emphasized that the Compton model, see [4], is based on the presumptions disputed by certain authors as they were not derived from the current electrodynamics principles. However, today this model is generally accepted since it is the only available model.

The Thompson classical electrodynamics assumed that the light is a wave by nature. The electron affected by such a wave should fluctuate with a frequency equal to the field frequency (i.e. wave length of the incident light) and radiate the secondary (scattered) waves of the same frequency. So, in the case of Thompson scattering, this process should not contain the waves of different frequencies. However, the research of X-ray scattering in paraffin made by Arthur Compton, see Fig. 3, demonstrated that X-rays scattered in paraffin have bigger wave length than the initial scattered rays. In other words, the radiation with both initial wave length and longer waves was detected.

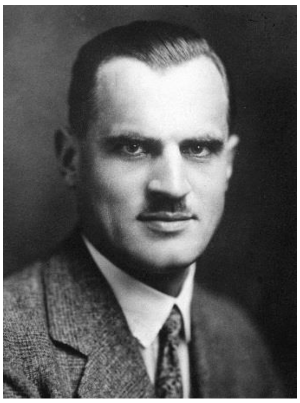

Fig 3: Arthur Holly Compton, Nobel Prize winner in physics

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Arthur Compton proposed the theoretical interpretation of this phenomenon (later it was independently proposed by Peter Debye) based on the corpuscular theory of light proposed by A. Einstein in 1905. Indeed, assuming that light radiation is a flow of particles – (corpuscles) photons, the Compton affect results from the elastic collisions between X-ray corpuscle – photons and free electrons of the substance. Since the light atoms of scattering substances (the paraffin in the experiment) are weakly connected to the nucleus, they can be deemed as free. Upon the collision, the photon transfers the part of its energy to the electron according to the law of conservation of energy. During this process, the partial loss of the photon energy is registered as the radiation frequency decrease (wave length increase) in the course of the experiment. Such wave length increasing was named Compton Shift. In 1927, A. Compton was announced as a Nobel Prize Winner for this discovery, confirming the double nature (wave-particle) of light.

The **E2** component is an intermediate (by the rise speed and length) HEMP component appearing as the secondary effect of the Compton electrons flow within the Earth's magnetic field. The E2 parameters have much in common with the electromagnetic pulses of aerial origin (i.e. generated by the lightning). The strength of the E2 field can reach 100 V/m. Since the E2 component is similar to the lightning and there are well-proven lightning protection technologies available, it is deemed that protection against the E2 component is very simple.

The **E3** (or a geomagnetic effect of HEMP) component is very much different from the two other HEMP components. It is a very slow pulse, lasting up to tens or hundreds of seconds and generated by the Earth's magnetic field shift and its following restoration. The E3 component is similar to the geomagnetic storm provoked by the very intensive solar burst. Geomagnetic induced currents are generated by the magnetic disturbances within the Earth's magnetosphere and flow in the ground.

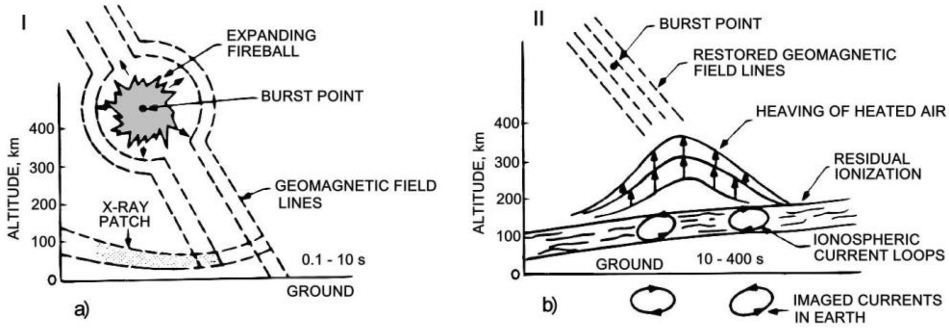


Fig 4: Two stages of a magnetohydrodynamic effect of HEMP [5]:

A) "blast wave" B) "heave"

The E3 component is based on the magnetohydrodynamic effects of interaction between the nuclear explosion plasma products and high-temperature ionized air with the magnetic field of the Earth. This effect has two stages called "blast wave" and "heave" and is characterized by different mechanisms of generation and length, see Fig. 4. The first stage lasts between to 1-10 seconds and is produced due to the expansion of large plasma substances generated in the thin air (at high altitude) under the influence of the Earth's magnetic field upon the explosion. This phenomenon is accompanied with the complex interaction between plasma ions, magnetic field, gamma, and X-radiation leading to the generation of the eddy electric field.

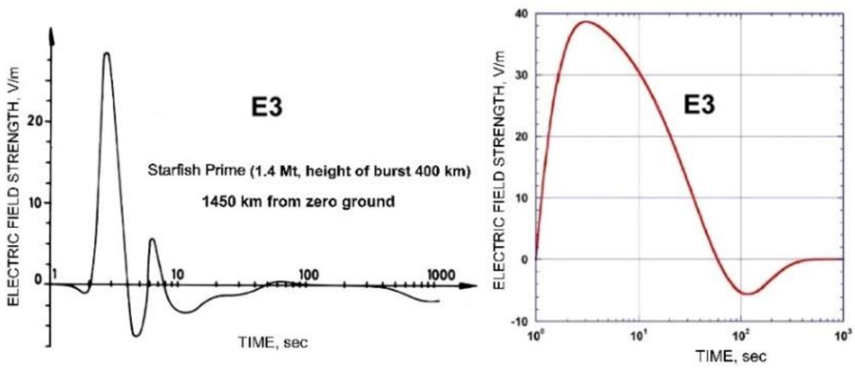


Fig 5: Variation of the horizontal component of the electric field near the Earth's surface upon the HEMP E3 impact. Left – pulse registered during the test explosion within Starfish Prime Project (1962 year); right – standard pulse (according to IEC 61000-2-9 [1]).

Those physical phenomena result in the significant disturbance of the Earth's magnetic field increasing with the increase of the explosion power and height above the ground. The second stage is characterized by the heave and hike of the ionized air (actually, plasma) overheated due to the explosion. When the ionized plasma crosses the Earth's magnetic-field lines, the air layer is polarized generating the high-power electric field creating the high circulating currents within the ionosphere, in its turn. Those processes are relatively slow. The second stage of explosion lasts from 10 seconds to 300 seconds.

Consequently, all those thin air processes generate the relatively slow varying magnetic field (from one to tens of Volts per km) near the Earth's surface, see Fig. 5.

Despite the low strength of the E3-generated electric field, it induces rather high electric currents with a very low frequency (less than 1 Hz) to the long metal objects (such as pipes, rails, power transmission lines). Such quasiconstant currents are dangerous for the power electric equipment not designed to operate under the constant currents (transformers, generators).

It should be noted that despite its danger regarding electronic and power electrical equipment, the energy of HEMP is rather low – less than 1% of the energy released upon the nuclear explosion. In any case, the HEMP energy is less than the energy released upon the lightning strike, see Fig. 6.

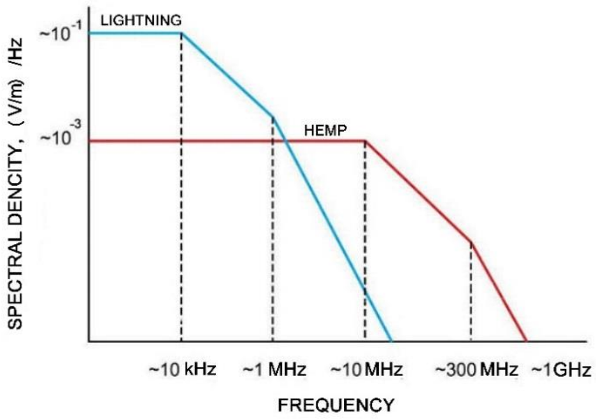


Fig 6: Lightning energy vs. HEMP energy

Thus, from the 1980s onwards, different countries of the world worked strenuously on the creation of the so-called nuclear Super-EMP with high-power electromagnetic radiation. Basically, the works are done in two directions: creating a core-shell made of a special substance additionally radiating the high-energy γ–rays (X-ray photons) under the influence of the nuclear explosion neutrons, and focalization of such γ –radiation. According to the experts, Super-EMP can significantly intensify the E1 component and create near the Earth's surface a field with a strength of hundreds and even thousands of kilovolts per meter. Moreover, the military officials make no secret that the government and military control systems, as well as national infrastructures, including power, water supply, etc., would be the primary targets for such a weapon in case of a conflict.

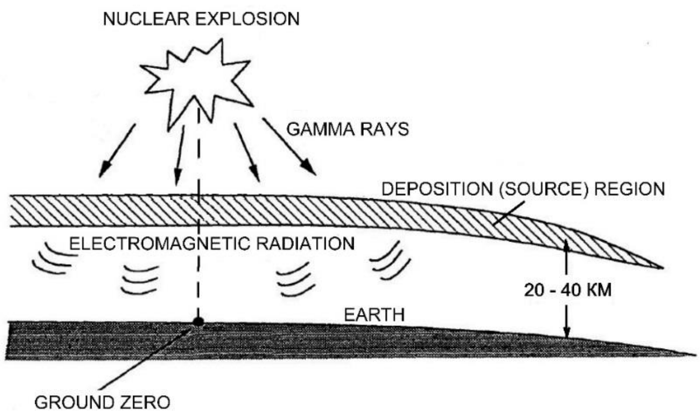
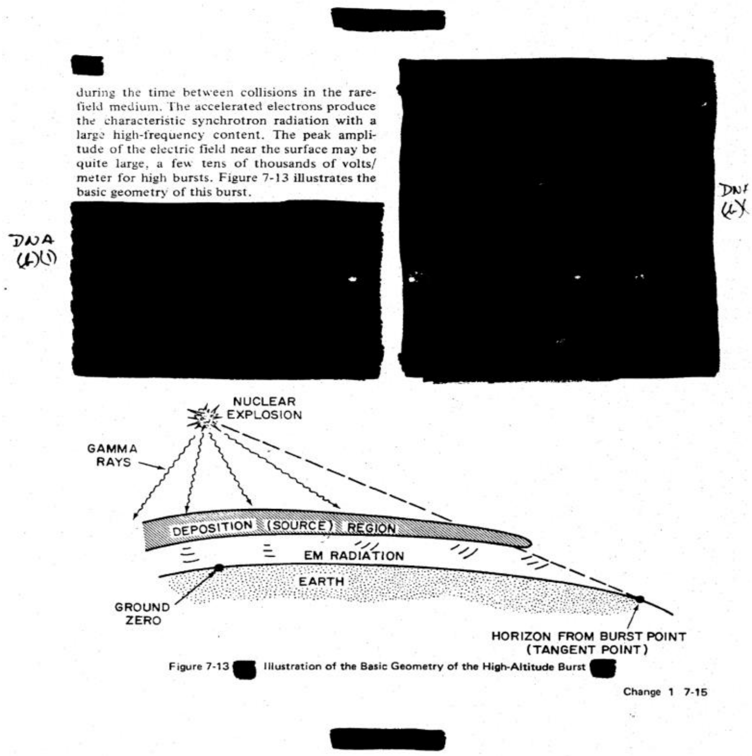


Fig 7: Generation of the electric field pulse near the Earth's surface upon the aerial nuclear explosion

Fig. 7 is repeatedly published in numerous reports and standards. Originally, it was taken from top secret report AD-A955391 [6] prepared 40 years ago, see Fig. 8.


[redacted]

[redacted] during the time between collisions in the rarefield medium. The accelerated electrons produce the characteristic synchrotron radiation with a large high-frequency content. The peak amplitude of the electric field near the surface may be quite large, a few tens of thousands of volts/meter for high bursts. Figure 7-13 illustrates the basic geometry of this burst.

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Figure 7-13 [redacted] Illustration of the Basic Geometry of the High-Altitude Burst [redacted]

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Fig 8: One page of fragmentary unclassified (more truly "sanitized" version with crossed-out labels "Top Secret" at the top and at the bottom of each page) version of report AD-A955391 ("Capabilities of Nuclear Weapons", DNA-EM-1, 1978); Chapter 7 of this report describes HEMP and its characteristics.

Since the E1 component is generally considered as the most dangerous for electronic and electrotechnical equipment, let us take a closer look at its properties and parameters.

The atmosphere has a special so-called source (or deposition) region located 20 km–40 km above the ground in the stratosphere. Here, the maximum number of X-ray electrons is generated under the influence of the above X-radiation and the secondary electrons knocked out the air atoms by Compton electrons, see Fig. 6. Each Compton electron has energy of about 1 Megaelectron Volt (MeV) and generates 30,000 secondary pairs of electron-ions knocked out of the air atoms along the way. Such pairs generate the above mentioned source region [7].

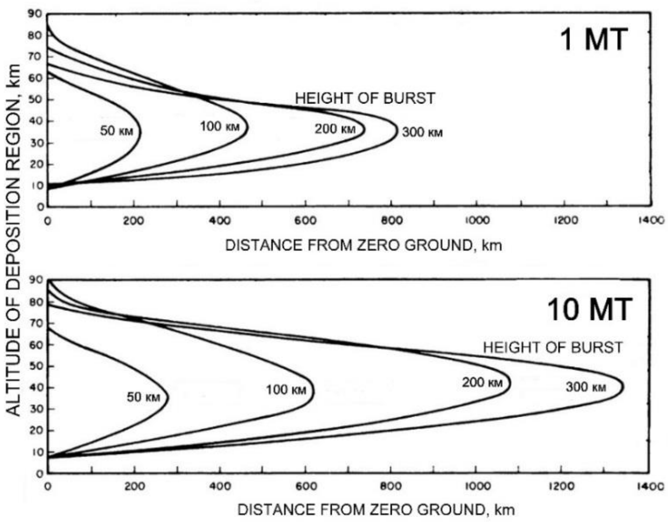

Fig 9: Expansion of Compton electron region in proportion to the nuclear yield and explosion height increasing: top – for 1 Mt yield; bottom — 10 Mt yield [8].

This region remains virtually steady height wise, but its radius increases significantly in proportion to the increasing yield of explosion and height of explosion, see Fig. 9 [8].

However, the air has different density at different heights, thus changing the properties of the generated electric field. It resulted that upon the high-altitude nuclear explosion in the very thin air, the number of atoms is low and therefore the number of generated free electrons is also low. Besides, the free electrons must travel to the Compton electron source region such a distance tha most of the such free electrons are able to recombine, and the electric field pulse near the ground surface weakens. On the contrary, upon the low-altitude nuclear explosion in the thick air (i.e. under the Compton electron source region) the number of such electrons reduces, the free electron travels to the ground surface, impedes, and is accompanied with the intensified recombination further weakening the electric field pulse near the ground. According to some data reflected in the unclassified reports, there is a certain optimal nuclear explosion height which allows reaching the maximum electrical field strength near the Earth's surface, see Fig. 10.

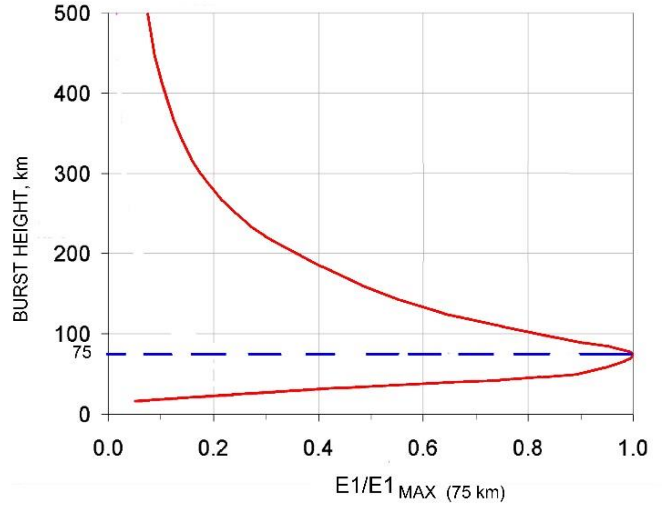

Fig 10: Dependence of the electrical field strength (E1) near the Earth's surface on the nuclear explosion height.

Nevertheless, since from the explosion point the X-radiation propagates along a straight line and does not depend on the curvature of the Earth, the EMP impact region radius is limited to the distance from the explosion point to the horizon. Definitely, the increase in the nuclear explosion height increases the region of HEMP impact on the surface electric equipment, see Fig. 11.

Fig 11: Dependence of HEMP impact region on the explosion height

However, the impact region is not equal to the damage region since the expansion of the HEMP impact region due to the explosion height increase is accompanied by the weakening of the electric field strength near the Earth's surface. Besides, it is obvious that the strength of such an electromagnetic field depends highly on the yield of a nuclear explosion, see Fig. 12. Also, the diagram shown in Fig. 12 demonstrates that the optimal explosion height is hardly a constant value. It increases in proportion to the yield of the nuclear explosion.

However, it transpires that there is even more. The experimental measurements of the electric field strength at different distances to the explosion epicentre showed a very strange tendency, see Fig. 13 [6]. Contrary to expectations and common sense, it transpired that the field strength is minimal immediately at the explosion epicentre (region A) while reaching its maximum somewhere outside the epicentre (region B, Fig. 13).

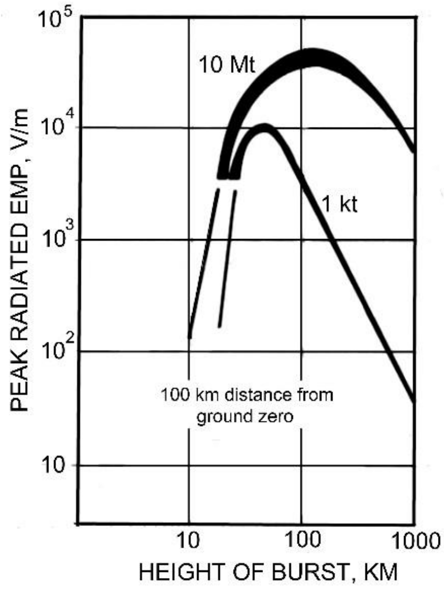

Fig 12: Dependence of the HEMP electric field strength on the height of the explosion and the yield of the explosion.

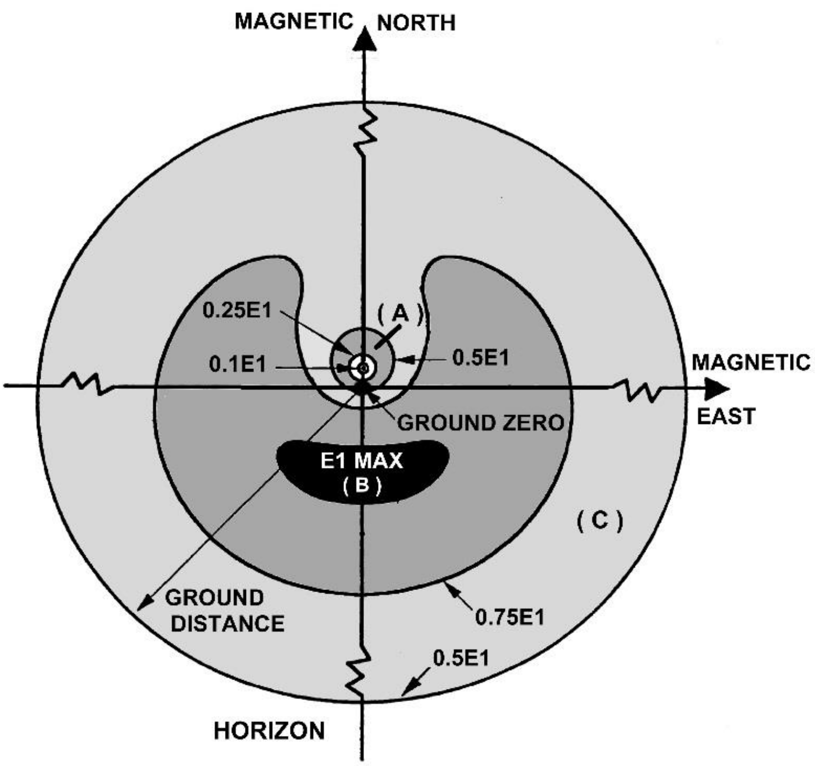

Fig 13: Distribution of the electric field strength (E1 of HEMP) at different distances to the epicentre (for the nuclear yield detonated at 100 km to 500 km with epicentre located between 30 and 60 degrees' north latitude) [6].

Additionally, the electric field strength amplitude has different values inasmuch as near the ground regions and the E1 pulse shape and length differs, see Fig. 14.

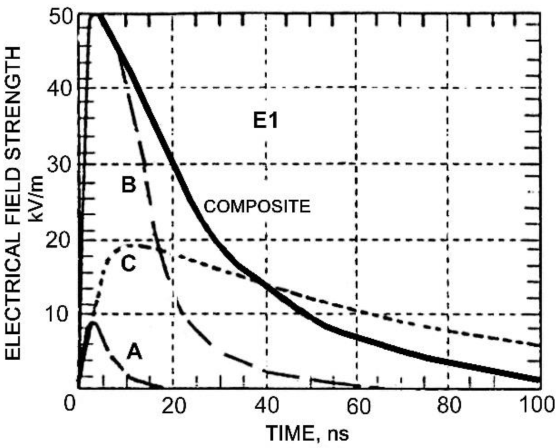

Fig 14: E1 electric field pulse shape and length in different regions on the ground surface.

Thus, a certain average curve of the E1 component, see Fig. 14, was calculated. Today, it is used as a standard curve of the E1 pulse of 2.5/23 (2.5/25) nanoseconds and amplitude of 50 kV/m, see Fig. 15. What is 2.5/25 nanoseconds? This is a special value characterizing the pulse shape.

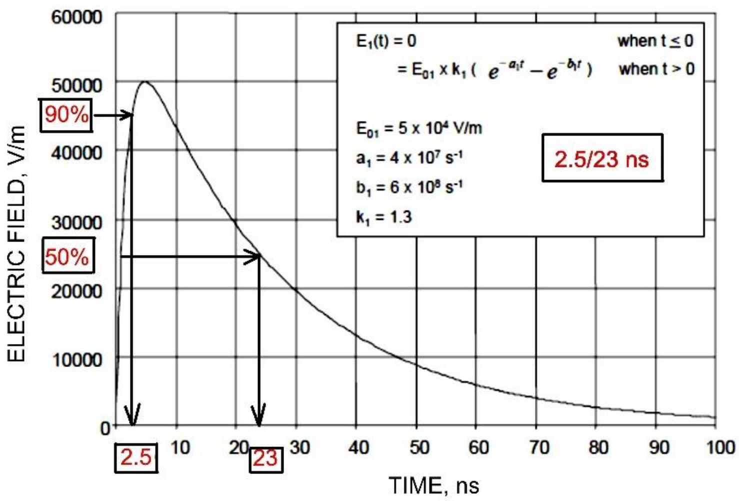

Fig 15: Standard shape of HEMP E1 pulse [6].

It is determined as the relation between the pulse rise time (front edge), calculated as the time when the pulse rises from 10% to 90% (2.5 nanoseconds) of amplitude value and the pulse full width at half maximum amplitude (23 nanoseconds or 25 nanoseconds in certain standards), see Fig. 16.

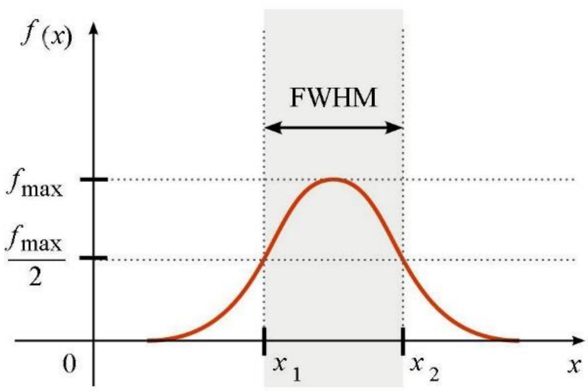

Fig 16: Meaning of "full width at half maximum" (FWHM) characteristic.

However, it took some time to make the proper calculations. Different authors proposed significantly different pulse parameters, see Fig. 17, Table 1.

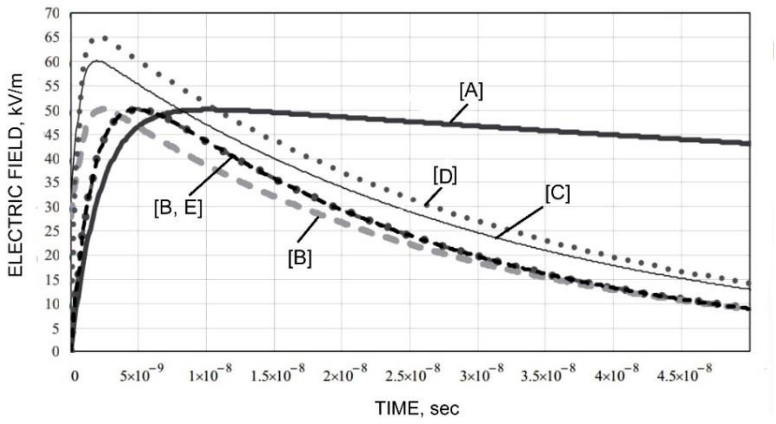

Fig 17: HEMP shape proposed by different authors at different times.

TABLE 1: HEMP PARAMETERS PROPOSED BY DIFFERENT AUTHORS AT DIFFERENT TIMES

Parameter Reference	**Bell Labs 1960 A [9]**	**Baum 1992 B [10]**	**Leuthäuser 1994 C [11]**	**VG95371-10 1995 D [12]**	**IEC 61000-2-9 1996 E [1]**
Peak Field, kV/m	50	50	60	65	50
Rise Time, ns	4.6	2.5	1.9	0.9	2.5
FWHM, ns	184	23	23.8	24	23
Energy Density, J/m	0.891	0.114	-	0.196	0.114

Finally, the version described in MIL-STD-464A and IEC 61000-2-9 Standards was generally accepted and the HEMP E1 pulse has the generally accepted shape shown in Fig. 15.

However, it is not all that simple as the pulse energy significantly depends on the pulse shape. This indicates that the lower pulse amplitude in region A, Fig. 13, does not mean that the energy has a lower value in the same region. The research carried out in [13] shows that it is most likely that this energy does not decrease see Fig. 18, as wider and smoother low-amplitude pulses have the same energy as shorter and steeper high-amplitude ones.

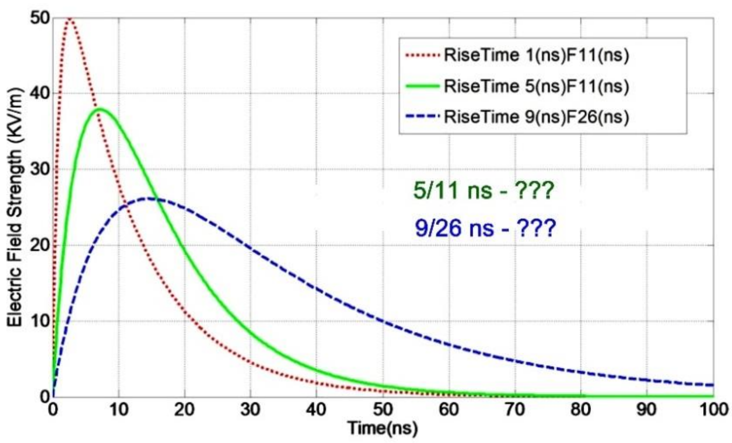

Fig 18: Calculated HEMP pulses of different shapes with the same energy.

It is worth noting here that values F (Fall Time) indicated by authors [13] (a trailing edge or a pulse-decay time) are not used to describe HEMP parameters (or lightning pulse). Instead, the so-called "full width at half maximum" or FWHM parameter is used. Moreover, even if the pulse-decay time (or time when the signal value decreases from 90% to 10% of an amplitude) is applied, the values shown at that diagram do not correspond to the diagrams themselves. Requesting all three authors of the article [12] for the explanation of the situation was unsuccessful: No answers were received.

Fourier transformation of a standard curve of the E1 pulse (see Fig. 19) according to [3], shows that within the range of 10kHz to 1MHz, the electric field strength stays relatively constant and maximum, and quickly decreases (almost by a factor of 100) when the frequency rises from 1MHz to 100MHz, and decreases even faster under the frequencies above 100MHz, see Fig. 19.

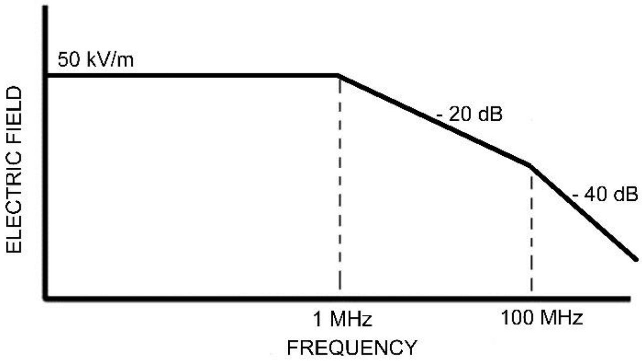

Fig 19: Distribution of the electric field strength within the frequency range under Fourier transformation of a standard E1 pulse.

Thus, HEMP frequency range in IEC 61000-2-9 [1] is defined within 100kHz–100MHz, where the pulse energy release reaches 96%, see Fig. 20.

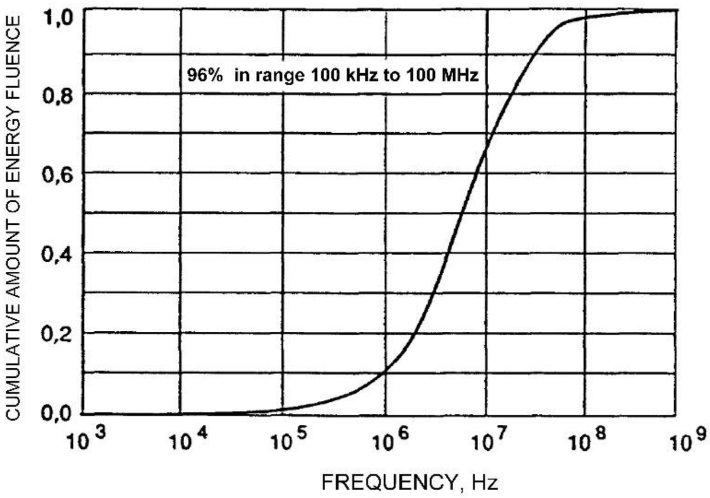

Fig 20: Distribution of energy within the HEMP frequency range [1].

In [14], see Fig. 21, an unusual but clearly evident definition of HEMP frequency range is depicted.

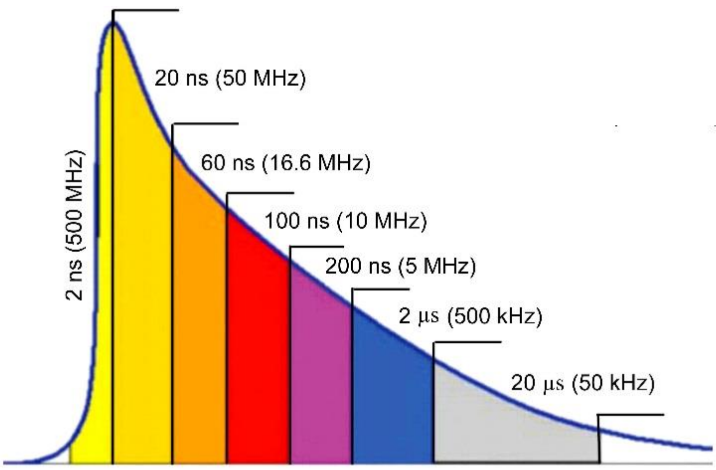

Fig 21: HEMP frequency range according to [13].

And if to narrow a power range up to 90 %, the frequency range of the HEMP will decrease up to limits 100 кГц - 10 MHz, Fig. 22 [15].

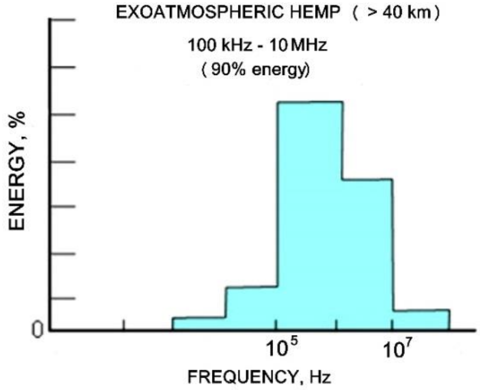

Fig 22: Energy distribution within the HEMP frequency range according to [15]

Such essential compression of frequency range of the HEMP in comparison with some statements in which HEMP frequency range reaches up to 1 GHz, is very important, as this range determines the major characteristics of shielding materials, elements and designs principles, and also the demand to them. Obviously, as also on frequency of 1 GHz is detected some part of HEMP spectrum, however, the contribution of this part to total energy of a HEMP is so insignificant, that it can be neglected.

Why does the electric field distribute so strangely (see Fig. 13) from the nuclear explosion epicentre? Since EMP generation depends largely on the magnetic field of the Earth, the answer is obvious: because of the Earth's magnetic field. The Earth's magnetic field has a rather interesting structure and shape. Prevalently, the Earth's magnetic poles do not match the geographical poles and show the tendency to the slow shift. Secondly, the magnetic field has a different value at the different points of the ground surface. The weakening of the magnetic field is accompanied with the decrease in HEMP intensity. Thirdly, the vectors of the horizontal and vertical components of the magnetic field induction have certain angles. The angle between the geographical and magnetic meridians at the defined point of the Earth's surface, demonstrating the difference between the magnetic compass readings and the true north direction at this point, is called the *magnetic declination* (or *magnetic variation*). The angle of the compass needle vertical deflection under the influence of the Earth's magnetic field is called the *magnetic inclination* (or *magnetic dip*). Also, in the Northern hemisphere, the needle tip pointing to the North goes down (to the Earth's surface), in the Southern hemisphere, it goes up. The magnetic inclination value is measured by a special device known as the *inclinator*.

Fig. 23 shows a map of isolines of the general magnetic field intensity on the surface of the Earth. Isoline – a line of points, where the measured characteristic has the same value in every point of the line.

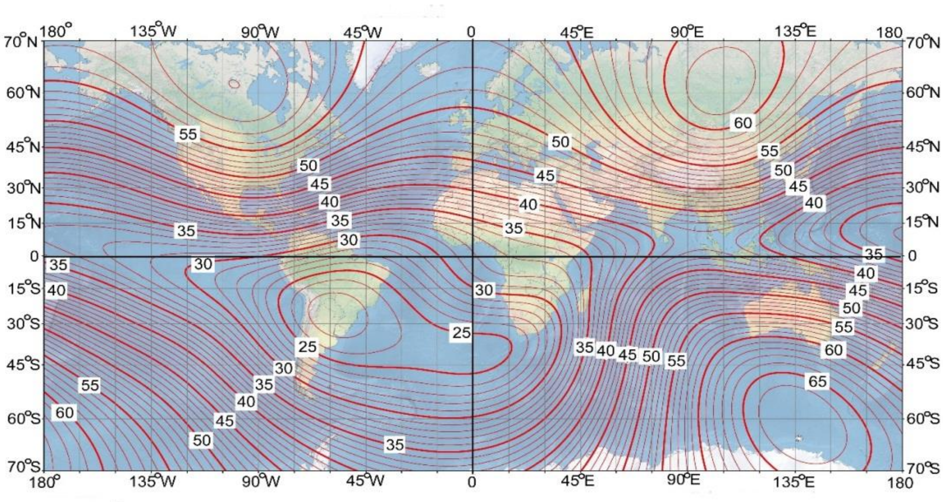

Fig 23: A map of isolines of the main magnetic field (μT) on the surface of the Earth.

Since, as was shown above, the Earth's magnetic field is directly involved in HEMP generation and this magnetic field is heterogeneous. The calculations presented in [16] demonstrate that the same yield of nuclear explosion, detonated at the same height, create at the Earth's surface an electromagnetic pulse that differs significantly in the amplitude of the electric field and in energy, depending on the location (geomagnetic latitude) of the epicentre of the explosion, see Fig. 24.

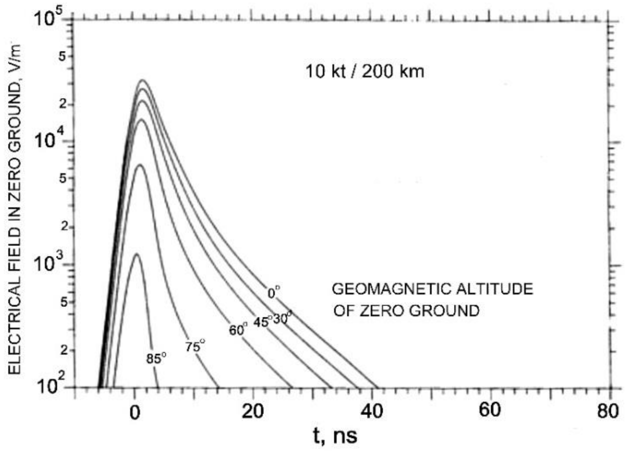

Fig 24: Variation of HEMP electric field strength as a function of latitude in the Northern hemisphere for a yield of explosion of 10 kt and detonation height of 200 km.

Since the HEMP pulse shape of 2.5/25 (2.5/23) nanoseconds described above related to the pulse of voltage applied to the apparatus, the situation becomes even more complicated. However, the current pulse starting to flow under the applied voltage pulse has an absolutely different shape: 10/100 nanoseconds (IEC 61000-5-3, IEC 61000-2-10), see Fig. 25.

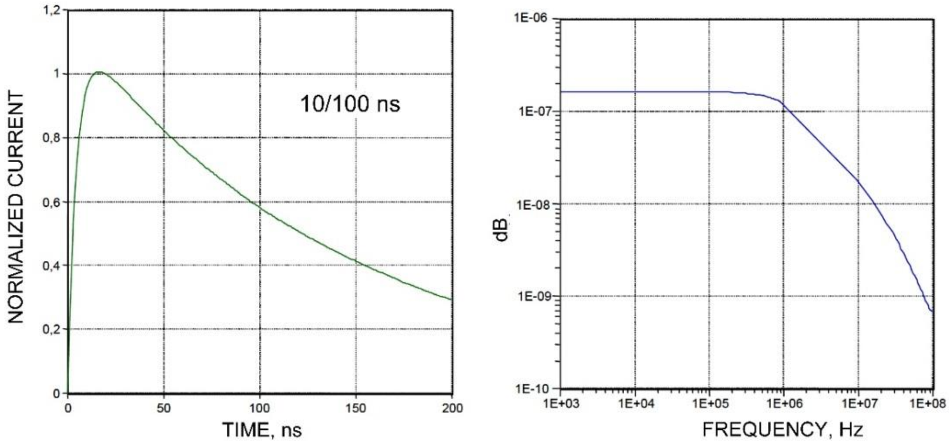

Fig 25: Standard shape of HEMP current pulse.

The shape of the current pulse depends heavily on the load conditions, i.e. on current circuit inductance and capacitance. It is obvious, that at change of length of a cable (wire) will change both current parameters: the shape of the current pulse and it amplitude, Fig. 26 [17].

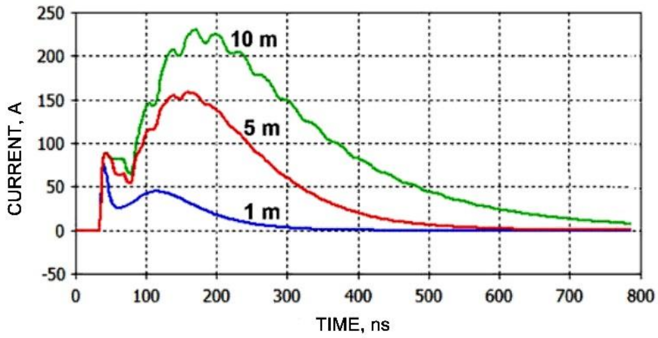

Fig 26: Dependence of current magnitude from cable length (1 to 10 m) at HEMP impact

However, in order to simplify the situation, the certain average standard current pulse shape with the parameters of 10/100 nanoseconds was accepted.

The situation is even more complicated with the buried electric cables, as the ground is a semiconducting environment providing the partial reflection of the falling electromagnetic wave, partially shunting the EMP. Obviously, the degree of the ground impact on the weakening of HEMP acting on the cable significantly depends on ground conductivity and the cable burial depth, see Fig. 27.

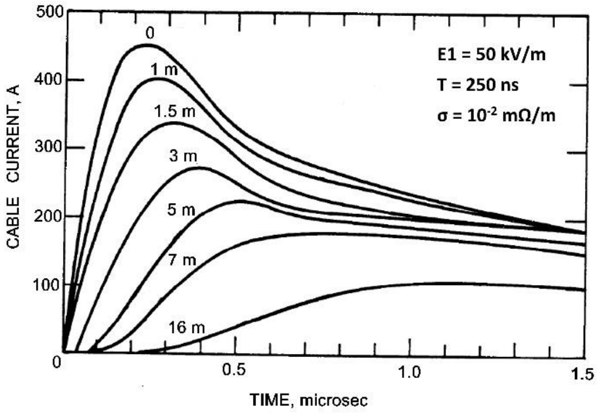

Fig 27: Dependence between the cable burial depth and the shape of the pulse applied by standard HEMP in the ground with a conductivity of σ =10^{-2} mOhm per meter.

According to the information mentioned above, it should be clear that HEMP values generally accepted in standards are averaged and generalized and do not reflect the real-life and real-device values. The only good thing here is that in most cases the standards show the worst-case values, so hopefully, the real-life HEMP would be less severe than those described in standards. Nevertheless, in 1985 the United States Department of Defense prepared the special standard MIL-STD-2169, repeatedly amended and corrected, where all above-mentioned relations were represented as graphic charts designed to calculate the HEMP impact on object operating under the different conditions. Unfortunately, today this standard remains classified.

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