Department of Energy

DATE: January 11, 2021

FOR: NATIONAL SECURITY COUNCIL RECORDS

FROM: Secretary of Energy Dan Brouillette

SUBJECT: Physical Characteristics of HEMP Waveform Benchmarks for Use in Assessing Susceptibilities of the Power Grid, Electrical Infrastructures, and Other Critical Infrastructure to HEMP Insults

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This memo is in response to the *Summary of Conclusions for the December 21, 2020 PSG Meeting on Benchmarks for Electromagnetic Pulses (EMP).*

This memo provides nuclear high-altitude electromagnetic pulse (HEMP) E1, E2 and E3 waveform recommendations for use by U.S. Government Agencies, industry, and other risk-holders in assessing potential HEMP susceptibilities for non-Department of Defense (DOD) Government agency and commercial sector specific electrical systems and other networked infrastructures across the sixteen critical infrastructure sectors. The following guidance is intended to fulfill Section 6 (b) (iii) of Presidential Executive Order 13865, March 26, 2019 on Coordinating National Resilience to Electromagnetic Pulses.

These waveforms are not hardening standards and do not specify the level of risk critical infrastructure faces from HEMP. The waveforms are representative of, and include uncertainties to account for, the threat from HEMP over the planned lifecycle of critical infrastructure investments (30-50 years). This memo is intended to be the first step in a long conversation with civilian stakeholders to begin to understand the threat, consequence, and risk associated with EMPs and how to address the risks.

These waveforms are intended to inform testing activities called for in EO 13865, including 6(b)(i), 6(b)(ii), 6(c)(i), and 6(c)(ii). Once testing is completed by DOD, the Department of Energy (DOE), the Department of Homeland Security (DHS), and others, the results will inform the DHS completion of an EMP risk assessment (EO 13865 5(f)(vii)). Once testing and the risk assessment are completed, DHS, DOD, and DOE will work to strengthen critical infrastructure, where necessary, to include the development of standards for protecting existing and new infrastructure. The development of standards will be done in consultation with the heads of other appropriate agencies and with the private sector as appropriate.

The National Security Council recommends that U.S. electrical systems and other critical infrastructure elements can be assessed for disruption and damage susceptibility up to the benchmark HEMP waveforms (described below) characterized by peak electric field strengths of 50 kV/m for E1, 100 V/m for E2, 80 V/km for E3a (blast), and 50 V/km for E3b (heave), respectively. The E1, E2, and E3 benchmark waveforms were developed using available information. DOD's benchmark waveforms are detailed in Appendix A.

Testing at electric field strengths up to the peak values will inform owners, operators, and risk holders of the aforementioned electrical systems and networked infrastructures on the operational margins under HEMP stress levels that exceed DOE's currently assessed threat levels by a factor of 2 due to predictive modeling uncertainties and potential excursions in HEMP environment levels. However, DOD recommends that the benchmark waveforms provided be used as the basis for susceptibility testing, vulnerability assessments, modeling, and simulation to understand where disruptions and damage could occur from HEMP insults. These results will enable risk-informed decisions to be made at a later date on what to protect (based on results from planned tests and assessments) and to what level of protection.

The recommended E1, E2, and E3 HEMP environment benchmark waveforms will be updated as necessary, based on further developments in our understanding of HEMP generation and modeling and simulation phenomenology.

ATTACHMENTS:

1. APPENDIX A: HEMP waveform benchmarks
2. APPENDIX B: Using the HEMP Benchmark Waveforms for Susceptibility Assessments
3. APPENDIX C: References

APPENDIX A

HEMP Waveform Benchmarks

E1 Waveform

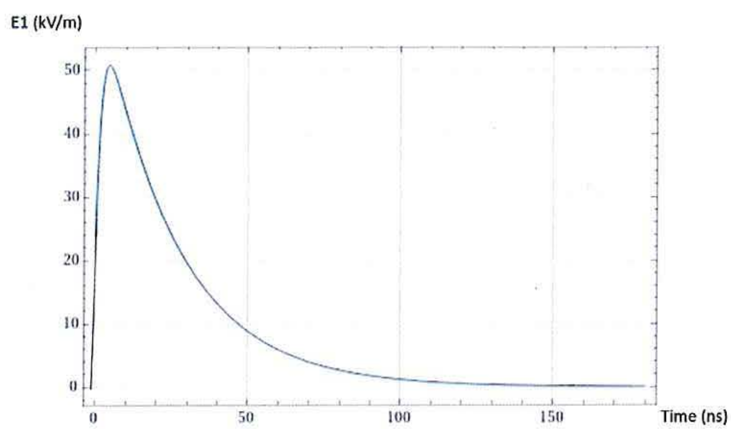
The early-time (E1) HEMP field waveform is given in the equation below as:

$$E1(t) = E_0 \cdot k(e^{-at} - e^{-bt}), \tag{1}$$

For time, $t > 0$, in seconds; and where the constants in the equation are given by $E_0 = 50\ kV/m$, $k = 1.3$, $a = 4 \times 10^7 s^{-1}$, $b = 6 \times 10^8 s^{-1}$.

This E1 waveform is the previously published IEC-61000-2-9 E1 waveform and is shown in figure 1 below.[1] There are no previously established U.S. benchmark waveforms for assessing susceptibilities of U.S. national critical infrastructures or the U.S. electric power grid to HEMP insults.

Use of the HEMP E1 incident waveform, as provided in figure 1, is recommended for evaluating the susceptibility of U.S. national critical infrastructures and the U.S. power grid, based on interagency policy discussions regarding present and future uncertainties.



$E1(t) = E_0 \cdot k(e^{-at} - e^{-bt})$

	E_0	k	$a\ (s^{-1})$	$b\ (s^{-1})$
Level	$50\ kV/m$	1.3	4×10^7	6×10^8

Figure 1. E1 benchmark waveform. E1 waveform equation coefficients are provided below the waveform.

The current Military Standard (MIL STD) for defense equipment as of December 2020 is 2169C. Those values will be considered for discussion with stakeholders when/if deemed appropriate.

Table 1. Historical comparison of E1 waveforms[1] (ranging from 50 to 60 kV/m peak field strength)

Parameter	Bell Labs (1960s) DEXP	Baum (1992) DEXP	Baum (1992) QEXP	IEC-77C (1993) DEXP	Leuthauser (1994) QEXP	VG95371-10 (1995) DEXP	IEC 6100-2-9 (1996)
$t_{10\%-90\%}$	4.6 ns	2.5 ns	2.4 ns	2.5 ns	1.9 ns	0.9 ns	2.5 ns
Peak Field E_0	50 kV/m	50 kV/m	50 kV/m	50 kV/m	60 kV/m	65 kV/m	50 kV/m
FWHM	184 ns	~23 ns	~24 ns	23 ns	23.8 ns	24.1 ns	23 ns
constant	1.05	1.3	1.114	1.3	1.08	1.085	1.3
α (1/sec)	4×10^6	4×10^7	1.6×10^9	4×10^7	2.20×10^9	3.22×10^7	4×10^7
β (1/sec)	4.76×10^8	6×10^8	3.7×10^7	6×10^8	3.24×10^7	2.07×10^9	6×10^8
Energy Density (J/m²)	0.891	0.114	0.107	0.114	0.167	0.196	0.114

E2 Waveform

The intermediate-time (E2) HEMP field waveform is given as:

$$E2\ (t) = E_0 \cdot (e^{-at} - e^{-bt})\ ,$$

For time, t > 0, in seconds; and where the constants in the equation above are given by $E_0 = 100$ *V/m*, $a = 1000\ s^{-1}$, and $b = 6 \times 10^8\ s^{-1}$.

The E2 waveform is characterized by an amplitude of 10 V/m to 100 V/m for times between approximately 0.01 μs and 1 ms.[i] The orientation of the E2 electric field is predominately orthogonal to Earth's surface.

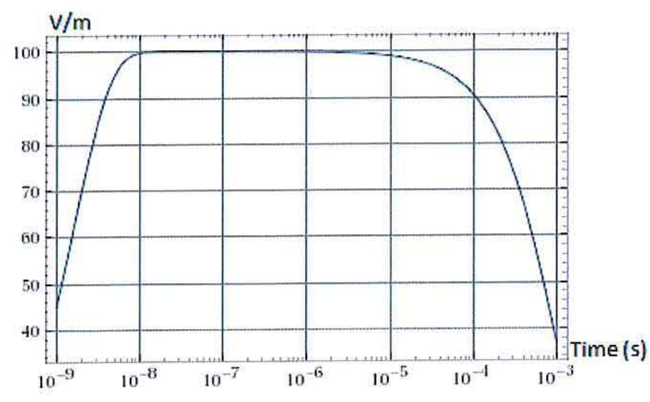


Figure 2. Recommended E2 benchmark waveform.

The current Military Standard (MIL STD) for defense equipment as of December 2020 is 2169C. Those values will be considered for discussion with stakeholders when/if deemed appropriate.

E3 Waveforms

The late-time E3 HEMP waveform is comprised of two separate waveforms, summed together, that are defined by differing late-time HEMP phenomenology considerations, and are represented by this equation

$$E_3(t) = E_{3a}(t) + E_{3b}(t)$$

These waveforms are defined as the E3a (blast waveform) and E3b (heave waveform), respectively, and are defined below. The E3a and E3b waveforms can be separated in time by several seconds, and the peak field strengths fall at different locations on the ground[ii,iii]

E3a – blast Waveform

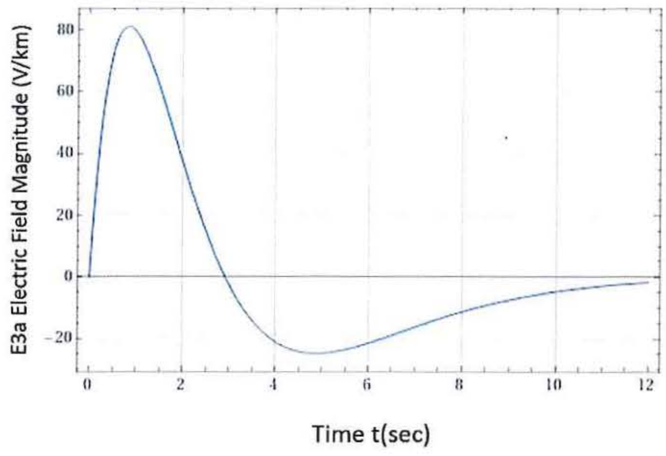
The late-time E_{3a} (blast) HEMP waveform (see figure 3) is based on earlier work by Oak Ridge National Laboratory (ORNL) and the EMP Commission,[iv,v,vi] and is given by the following curve-fit based equation in units of V/km,

$$E_{3a}(t) = \alpha e^{-t/\beta}(\gamma t - \delta t^2)$$

for t > 0, in seconds; and where the constants in the equation are given by,

$\alpha = 9.5$,
$\beta = 1.4$,
$\gamma = 26$, and
$\delta = 8.9$

The E_{3a} (blast) waveform applies for $t > 0$, where $E_{max} = 80$ V/km, and a ground conductivity of 10^{-3} S/m that is suitable for a mid-latitude Continental United State (CONUS) location of 40° N. The peak E3a field strength can vary depending on the latitude under consideration and the local ground conductivity values, and further guidance on how to account for these effects is provided below.



$E_{3a}(t) = \alpha e^{-t/\beta}(\gamma t - \delta t^2)$, in units of V/km for t (secs)

	α	β	$\gamma\ (s^{-1})$	$\delta\ (s^{-2})$
Level	9.5	1.4	26	8.9

Figure 3. E3a–blast benchmark waveforms to be used for susceptibility testing. E3a–blast waveform equation constant coefficients are provided below the waveforms, in the table above.

The current Military Standard (MIL STD) for defense equipment as of December 2020 is 2169C. Those values will be considered for discussion with stakeholders when/if deemed appropriate.

E3b – heave Waveform

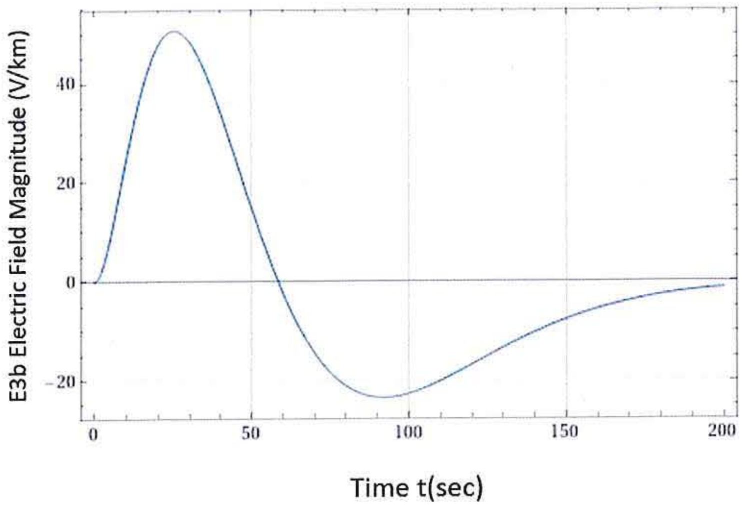
The late-time E_{3b} (heave) HEMP waveform is given by the following curve-fit based equation in units of V/km,

$$E_{3b}(t) = -\alpha t^2 e^{-t/\gamma}\frac{\beta^3 t - 3\beta^3\gamma + t^4}{\gamma(\beta^3 + t^3)^2}$$

For time, t > 0, in seconds, and where the constants in the equation are given by,

$\alpha = 13 \times 10^5$,
$\beta = 200$, and
$\gamma = 20$

The E_{3b} (heave) waveform applies for $t > 0$, a ground conductivity of 10^{-3} S/m and a mid-latitude CONUS location of 40° N.[vii] This recommended E_{3b} waveform represents a change relative to the previous international waveform;[viii] and it applies for $t > 0$, where $E_{max} = 50$ V/km.



$$E_{3b}(t) = -\alpha t^2 e^{-t/\gamma} \frac{\beta^3 t - 3\beta^3\gamma + t^4}{\gamma(\beta^3 + t^3)^2}$$, in units of V/km for t (secs)

	α	β	γ
Level	13×10^5	200	20

Figure 4. E3b benchmark waveform to be used for susceptibility testing. E3b (heave) waveform equation coefficients are provided below the waveform, in the table above.

The current Military Standard (MIL STD) for defense equipment as of December 2020 is 2169C. Those values will be considered for discussion with stakeholders when/if deemed appropriate.

APPENDIX B

Using the HEMP Benchmark Waveforms for Susceptibility Assessments

Existing HEMP testing protocols may be used to evaluate susceptibilities for sector or enterprise-specific electronics and networked infrastructure elements to the E1, E2, and E3 benchmark HEMP waveforms. Additional information on existing HEMP waveform testing approaches can be found in the HEMP IEC 61000-series[ix,x] and DOD Mil-Standards[xi,xii,xiii] and Handbooks[xiv] to assess HEMP resilience.

The National Security Council recommends infrastructure owners, operators, and risk holders use suitable HEMP coupling models and test data, as appropriate, to determine component and system susceptibilities attributable to the currents and voltages induced within their infrastructure elements following exposure to the recommended incident E1, E2, and E3 HEMP benchmark waveforms. For E3 coupling assessments, infrastructure owners and operators should incorporate local ground conductivity values, such as those provided by current and future magnetotelluric surveys,[xv,xvi] and account for latitude effects on the induced current and voltage loading on hardware connected to long conductive lines.

DOE recommends that select electronics and energy infrastructure element hardware be tested starting at low peak field strength levels, for example equivalent to 1 kV/m, and then at increasing values to determine the levels at where disruption and damage occur.

Disruption and damage effects observed during testing at each insult level should be evaluated and documented. For awareness, DOE, DOD Defense Threat Reduction Agency, and other organizations have archives of HEMP test data and assessment reports of various electrical and energy infrastructure elements that can be made available as appropriate, and in addition some relevant information can also be found in open publications. For each of the selected test levels, the local effects and results observed at the component level should be documented and then integrated into the overall response of the networked infrastructure through modeling- and simulation-based assessments to determine the predicted system-wide response and effect(s). These modeling efforts, vulnerability and consequence assessments, and associated test data should be safeguarded and shared with U.S. Government agencies, including the Department of Homeland Security, or their delegates, as appropriate. Each vulnerability evaluation and hardening decision will likely be unique to that particular infrastructure element and involve the relevant owners, operators and risk holders.

The U.S. government will provide, by early 2021, general technical guidance to National Laboratories and other expert organizations on how energy sector-specific and other owners, operators, and risk holders can conduct HEMP susceptibility testing and assessments, and how to safeguard and share those data and assessments with relevant U.S Government Agencies.

APPENDIX C: References

[i] IEC Ref. No. EN 61000-2-9, https://webstore.iec.ch/publication/4141

[ii] Dyal, Palmer (2006). "Particle and field measurements of the Starfish diamagnetic cavity." Journal of Geophysical Research: Space Physics 111.A12.

[iii] Meta-R-321, The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, January 2010.

[iv] ORNL/Sub/90-SG828/1, Magnetohydrodynamic Electromagnetic Pulse (MHD-EMP) Interaction with Power Transmission And Distribution Systems, February 1992.

[v] EMP Commission, Recommended E3 HEMP Heave Electric Field Waveform for the Critical Infrastructures, July 2017.

[vi] Dyal, Palmer (2006). "Particle and field measurements of the Starfish diamagnetic cavity." Journal of Geophysical Research: Space Physics 111.A12.

[vii] IEC Ref. No. EN 61000-2-10 Ed. 1.0 (1998-11): Electromagnetic Compatibility (EMC) – Part 2-10: Environment – Description of HEMP Environment – Radiated disturbance, Basic EMC publication.

[viii] IEC Ref. No. EN 61000-2-10 Ed. 1.0 (1998-11): Electromagnetic Compatibility (EMC) – Part 2-10: Environment – Description of HEMP Environment – Radiated disturbance, Basic EMC publication.

[ix] IEC Ref. No. EN 61000-2-9; Electromagnetic compatibility (EMC) - Part 2: Environment - Section 9: Description of HEMP environment - Radiated disturbance; 1996.

[x] IEC Ref. No. EN 61000-2-10; Electromagnetic compatibility (EMC) –Part 2-10: Environment – Description of
HEMP environment – Conducted disturbance; 1998.

[xi] Mil-Std 188-125

[xii] Mil-Std 3023

[xiii] Mil-Std 464C, ELECTROMAGNETIC ENVIRONMENTAL EFFECTS REQUIREMENTS FOR SYSTEMS, 1 Dec 2010.

[xiv] Mil-Hdbk-423

[xv] USGS; Report; published March 5, 2019; New U.S. Geological Survey Report Assesses Risk of Once-Per-Century Geomagnetic Superstorm to the Northeastern United States; at https://www.usgs.gov/news/new-us-geological-survey-report-assesses-risk-once-century-geomagnetic-superstorm-northeastern; site accessed May 5, 2020.

[xvi] Oregon State University; Paper presented at Space Weather Workshop, Boulder CO 3-April-2019; Integrating space weather and ground-based magnetotelluric data with powerflow solutions for real-time assessment of risk to the power grid; at https://www.swpc.noaa.gov/sites/default/files/images/u59/02%20Adam%20Schultz%20Official.pdf; site accessed May 5, 2020.