# **Executive Summary**: ***High-altitude Electromagnetic Pulse (HEMP): A Mortal Threat to the U.S. National Power Grid and U.S. Nuclear Power Plants***

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**High-altitude Electromagnetic Pulse (HEMP): A Mortal Threat to the U.S. National Power Grid and U.S. Nuclear Power Plants**

A nuclear weapon detonated in the upper atmosphere will produce a High-altitude Electromagnetic Pulse (HEMP).[1] While no blast, fires, or ionizing radiation will be felt on Earth, a single HEMP will instantly create intense electromagnetic fields that will blanket tens or hundreds of thousands of square miles of the Earth's surface. These fields will induce highly destructive transient electric voltages and currents into any electrically conductive material located in the affected regions, including overhead power transmission lines, telecom lines, and cables. Any unshielded modern electronic equipment, containing solid state circuitry connected to these lines, will be damaged or destroyed.

A single HEMP can also damage or destroy the majority of the Large Power Transformers (LPTs) and high-speed circuit breakers in entire regions of the United States. Because it takes up to two years to replace LPTs, one HEMP would bring down most or all of the U.S. national electric grid for a year or longer. HEMP will also knock out much of the U.S. critical national infrastructure through the destruction of the integrated circuits (microchips, logic circuits, and solid-state components) that are found within almost all modern electronic devices. HEMP would also disable the emergency power systems and Emergency Core Cooling Systems (ECCS) at U.S. nuclear power plants. A single HEMP could cause the meltdown of dozens of commercial nuclear reactors, which were not designed to withstand HEMP. The meltdown of these reactors could leave much of the U.S. too radioactive to live in for centuries.



[1] The nuclear weapon can be carried by *a ballistic missile, a satellite, or a high-altitude balloon.*

***Effects of HEMP on the National Electric Grid***

In a timespan measured in a few billionths of a second, the E1 component of HEMP can induce peak voltages of 2 million volts into long overhead medium-voltage power lines, which can create a current of 5000 amps in these lines.[2] These high voltages and currents will destroy tens of millions of insulators on power distribution lines.[3] The subsequent E3 component of HEMP, which occurs a number of seconds after E1, would destroy or disable a majority of the Large Power Transformers (LPTs) and high-voltage circuit breakers that are required for long distance transmission of power in the U.S. national electric power transmission network (the "grid").[4] LPTs make up less than 3% of transformers in U.S. power substations, but they carry 60%-70% of the nation's electricity.[5]

Scientists have confirmed, by "*all means of measurement*", that "*the threat potential posed by HEMP exceeds the intended stress limit that the U.S. power network is designed and tested to withstand"*[6] (this is also true for the effects created by an extreme Geomagnetic Disturbance or GMD,[7] which are quite similar to those created by the E3 component of HEMP).

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[2] The worst-case HEMP E1 used by the military in MIL-STD-188-125-1 for an E1-induced powerline current of 5,000 amperes. The characteristic impedance for a power line is approximately 400 ohms, thus providing a peak worst-case voltage level of 2 MV. Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 7-3.

[3] Personal correspondence with Dr. William Radasky, January 9, 2022.

[4] There are about 2,000 LPT's in the US rated at or above 345 kV, see Gilbert, J., Kappenman, J., Radasky, E., Savage, E. (January 2010), "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", Metatech Corporation, Meta-R-321, p. 2-32. http://www.futurescience.com/emp/ferc_Meta-R-321.pdf

[5] Parfomak, P. (June 17, 2014). "Physical Security of the U.S. Power Grid: High-Voltage Transformer Power Stations:", Congressional Research Service, CRS Report Prepared for Members and Committees of Congress. P. 1.

[6] Gilbert, J., Kappenman, J., Radasky, W. (2010). "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", Metatech Corporation, Meta R-321. P. 3-2. https://www.futurescience.com/emp/ferc_Meta-R-320.pdf

[7] A massive Geomagnetic Disturbance, or Coronal Mass Ejection (CME), would have the same general effect as the E3 component of HEMP. It is beyond the scope of this paper to discuss CME although it will receive some mention.

A single HEMP would likely damage or destroy the majority of LPTs in the U.S national electric grid[8] or those in an entire geographic region, such as the eastern half of the United States.[9]

Thus, one HEMP (or massive GMD) would certainly leave either all the U.S. or entire regions of the U.S. without electric power – *and power would not return for months or years*. This is because (1) it will take that long to manufacture and replace many millions of insulators used on power distribution lines and (2) LPTs are not stockpiled and typically must be custom designed by specially trained engineers, assembled by experienced technicians, have extremely exacting technical specifications, and require extensive testing. There are only 8 companies in the U.S. currently manufacturing LPTs,[10] however, it might prove to be impossible to domestically manufacture LPTs if all or most of the U.S. national electric grid was down. Replacement LPTs and insulators would have to be imported if they had not been stockpiled.

Prior to 2020, the U.S. had to import 82% of its LPTs.[11] The lead time for LPTs manufactured overseas is currently 12 to 18 months.[12] LPTs weigh between 100 to 400 tons;[13] imported LPTs must be shipped by sea freight (too heavy for air freight), which extends shipping times.[14] Transporting huge LPTs to installation points is time consuming and difficult and may add additional months before they can be put into service. If HEMP destroys many or most of the

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[8] Gilbert, J., Kappenman, J., Radasky, W. (2010). "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", Metatech Corporation, Meta R-321, p. 4-12. https://securethegrid.com/wp-content/uploads/2020/01/Metatech-Meta-R-321.pdf

[9] Ibid, pp. 3-5 through 3-12.

[10] Behr, P. (Oct 20, 2022), "How a transformer shortage threatens the grid". E&E News, Energy Wire, https://www.eenews.net/articles/how-a-transformer-shortage-threatens-the-grid/

[11] Postelwait, J. (July 12, 2022). "Transformative Times: Update on the US.S. Transformer Supply Chain", T&D World, https://www.tdworld.com/utility-business/article/21243198/transformative-times-update-on-the-us-transformer-supply-chain

[12] Distributech International, Powergrid International, Dec 21, 2022, "Inaction on electric transformer crisis adds reliability concerns, APPA warns". https://www.power-grid.com/td/inaction-on-electric-transformer-crisis-adds-to-reliability-concerns-appa-warns/#gref

[13] U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability. (April 2014). "Large Power Transformers and the U.S. Electric Grid", p. vi. https://www.energy.gov/sites/prod/files/2014/04/f15/LPTStudyUpdate-040914.pdf

[14] Op. cit. "Transformative Times: Update on the US.S. Transformer Supply Chain"

LPTs in the U.S. national power grid, *it will likely take at least a year or longer to restore electric power to entire geographic regions in the U.S.*

***Effects of HEMP on Critical National Infrastructure***

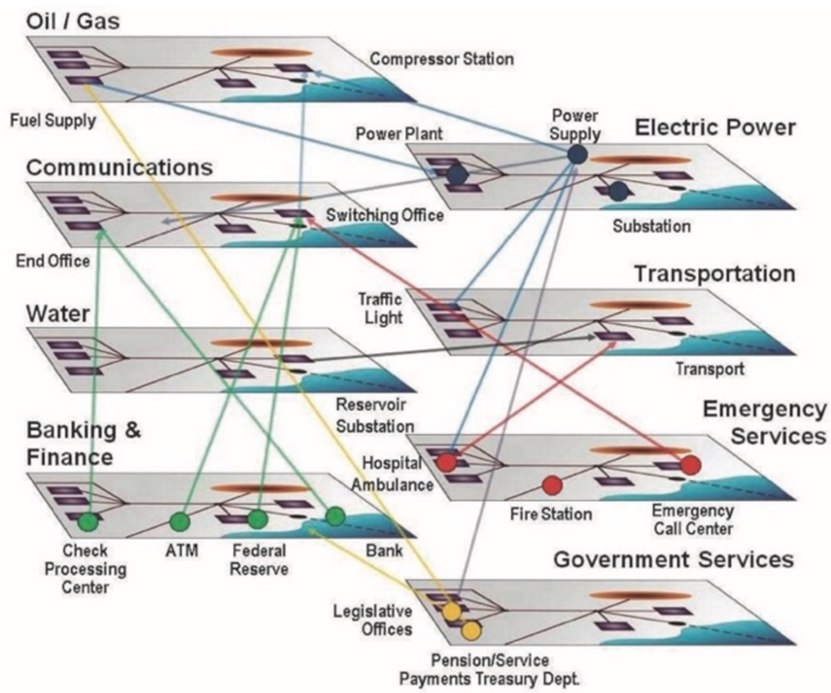


Figure 1: A Conceptual Illustration of the Interconnectedness of Elements Contained Within Each Critical Infrastructure. Some connections are not shown (diagram originally from Sandia National Laboratory).[15]

The E1 component of HEMP can also disable, damage, or destroy any unprotected integrated circuits and control panels within the electronic equipment that is essential to the operations of critical national infrastructure.[16] Throughout large geographic regions, HEMP would not only stop the delivery of electric power, but it would also wreck the solid-state electronics and integrated circuits *inside* the modern electronic equipment required to operate:

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[15] Critical National Infrastructures. (April 2008). "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack", Chapter 1, page 12. http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf

[16] Commercial companies normally cannot afford to place all of their electronics in highly shielded buildings as prescribed by the U.S. military. Radasky, W. (October 31, 2018). "Protecting Industry from HEMP and IEMI", *In Compliance Magazine.* https://incompliancemag.com/article/protecting-industry-from-hemp-and-iemi/

- ground, sea, rail, and air transportation systems
- fuel and food distribution systems
- water and sanitation systems
- telecommunication systems
- banking systems and electronic financial transactions
- emergency services and governmental services

In addition to the time required to restore electric power, it would also take months to test and replace all the damaged solid-state circuitry and microchips *within* the electronic devices required by these systems (assuming replacement parts were available) before most critical national infrastructure could resume normal operations.

Without electric power from the grid, U.S. citizens would quickly find themselves without running water, food and refrigeration, lights, functioning toilets and sewage systems, air conditioning and heating, transportation, phones, and communication systems, as well as access to their bank accounts or medical services.[17] In other words, a single HEMP (or massive GMD) would create complete chaos leading to societal collapse. And this would likely be the case for any nation that has not taken significant steps to protect its national infrastructure from the effects of HEMP (as well as GMD).[18]

***Effects of HEMP E1 on Nuclear Power Plants and Nuclear Reactors***

The U.S. Nuclear Regulatory Commission (NRC) considers U.S nuclear power plants to be in no danger from EMP.[19] The NRC views EMP as a "beyond-design-basis event", which



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[17] Ibid, Chapter 2, page 17. Excerpt: "For most Americans, production of goods and services and most of life's activities stop during a power outage. Not only is it impossible to perform many everyday domestic and workplace tasks, but also people must divert their time to dealing with the consequences of having no electricity. In the extreme, they must focus on survival itself. The situation is not different for the economy at large. No other infrastructure could, by its own collapse alone, create such an outcome."

[18] More than 50 nuclear reactors could meltdown in France from the effects of a single HEMP.

[19] Nuclear Regulatory Commission. (December 2011). "Resolution of Generic Safety Issues: Issue 20: Effects of Electromagnetic Pulse on Nuclear Power Plants (Rev. 1) (NUREG-0933, Main Report with Supplements 1–35)". https://www.nrc.gov/sr0933/index.html

does not have to be protected against with the use of "safety-grade systems, structures, and components."[20] Consequently, no U.S. nuclear power plant (currently under license) has been designed, constructed, or retrofitted to survive an EMP attack.

The Electromagnetic Defense Task Force (EDTF), created by members of the U.S. Air Force Air University, has questioned the NRC about the lack of credible research and comprehensive physical testing of the impacts of EMP on U.S. nuclear power plants. A 2019 report published by the EDTF listed several serious concerns, including a prolonged "station blackout" (a complete loss of off-site and on-site electric power, due to the impact of HEMP on both the national electric grid and the emergency power systems at U.S. nuclear plants). The EDTF took the position that *all* electronic devices are subject to EMP, yet the NRC requires no testing of any electronics located in the emergency power systems, the emergency core cooling systems, or within the control panels that govern these systems.[21]

U.S. nuclear power plants rely on numerous systems that require a host of electronic devices (control units, rectifiers, inverters, switches, motor-driven pumps, motor-operated valves, temperature and pressure sensors, etc.) to monitor, control, and safely operate their nuclear reactors and spent fuel pools (where highly radioactive used uranium fuel is stored). These electronic devices obviously require electric power to operate; they also contain unshielded solid-state electronics that are highly susceptible to damage from the high voltages and currents induced by HEMP E1. These devices are located *within* the various components that comprise the emergency backup power systems and the active Emergency Core Cooling Systems



[20] Stuckenberg, D., Woolsey, J., DeMaio, D. (August 2019). "Electromagnetic Defense Task Force (EDTF) Report 2.0, LeMay Paper No. 4", Air University Press, Maxwell Air Force Base, Alabama, Appendix 1, pp. 53. https://www.airuniversity.af.edu/Portals/10/AUPress/Papers/LP_0002_DeMaio_Electromagnetic_Defense_Task_Force.pdf
[21] Ibid, p. 59.

(ECCS) – which will be left inoperable if there is no electric power and/or if the solid-state electronics within them are disabled.

Moments after HEMP brings down the grid, the loss of off-site power would cause nuclear plants to shut down on an emergency basis. While emergency shutdowns do not require electrical power, the shutdowns would be followed by an immediate failure of the plants' backup emergency power systems, as well as the active ECCS systems that require electricity and functioning motor-driven pumps, control units, sensors, and motor-operated valves to operate. HEMP E1 damage would disable many of the various components that comprise these emergency systems and render them inoperable.

A large commercial nuclear reactor operating at full power will still have hundreds of millions of watts of residual decay heat in the core after emergency shutdown (decay heat produced by radioactive fission products in the fuel rods). The core must be rapidly cooled in a matter of minutes; without functioning emergency power and active ECCS, the core will overheat and self-destruct in a matter of hours or at most a few days (this is essentially what happened to Units 1, 2 and 3 at Fukushima Daiichi[22]).

Without backup electric power, cooling the reactor core becomes impossible. Without power, it is also impossible to maintain system control, lighting, communication, as well as ventilation to the reactor, to the emergency diesel generators[23], and to the ancillary plant[24]. And even with electric power, the active components of the ECCS cannot function if the integrated circuits and solid-state components within the ECCS are disabled by HEMP E1.

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[22] World Nuclear Association. (May 2022). "Fukushima Daiichi Accident, Event sequence following earthquake". https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-daiichi-accident.aspx

[23] EDGs have to start reliably and quickly and under any condition and must be able to take on load almost instantaneously, which generally means within about 10 Seconds. QuantiServ. (January 26, 2021). https://www.quantiserv.com/2021/01/26/nuclear-power-plant-emergency-generator-engine-block-repair/

[24] Auxiliary of power plant is ancillary equipment, such as pumps, fans, and soot blowers, used with the main boiler, turbine, engine, waterwheel, or generator of a power-generating station.

A failure of the ECCS to remove heat from the reactor core can cause the temperature in an uncooled reactor core to rapidly reach 1230 degrees Celsius (2246 degrees Fahrenheit), at which point the fuel rods will self-destruct. In the absence of cooling, the fuel rods and control materials in the core will begin to melt, leading to the complete destruction of the reactor core.[25] Because the high voltages and currents induced by E1 from a single HEMP could damage and destroy solid-state electronics in an area of tens of thousands of square miles, a well-placed HEMP cut hit dozens of nuclear reactors at US nuclear power plants located within an E1-affected region and they could all experience simultaneous core meltdowns (Figure 2).

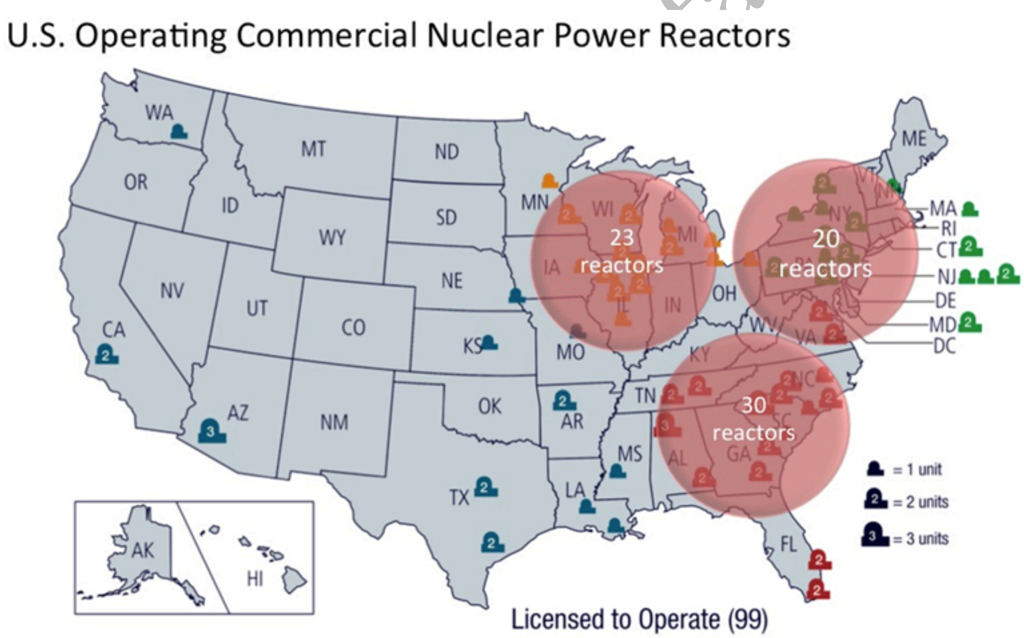


*Figure 2:* The number of operating nuclear reactors (20 to 30 in each zone) that would be within the areas predicted to have HEMP E1 levels of 12,500 volts per meter or greater**;** each zone created by one 500-kiloton warhead detonated at an altitude of 75 km (42 miles).[26]

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[25] "In the absence of a two-phase mixture going through the core or of water addition to the core to compensate water boiloff . . . In less than half an hour, the peak core temperature would reach !100 K. At this temperature, the zircaloy cladding of the fuel rods may balloon and burst." *Kuan, P., Hanson, D. J., Odar, F. (1991). "Managing water addition to a degraded core."* U.S. Department of Energy Office of Scientific and Technical Information, OSTI 5642843, p. 4. https://www.osti.gov/servlets/purl/5642843

[26] Map of nuclear power plants from the NRC https://www.nrc.gov/reactors/operating/map-power-reactors.html based upon the data on Peak E1 provided by the Metatech Corporation. Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-30.

Other nations beside the U.S. appear to have not shielded their nuclear reactors from HEMP. France could have *all* of its nuclear reactors at risk from a single HEMP (from a non-Super EMP nuclear weapon). One HEMP would blanket all of France with E1 incident energy fields capable of disabling the emergency power systems and Emergency Core Cooling Systems at *every* French nuclear power plant (Figure 3). This would leave France an uninhabitable radioactive wasteland.

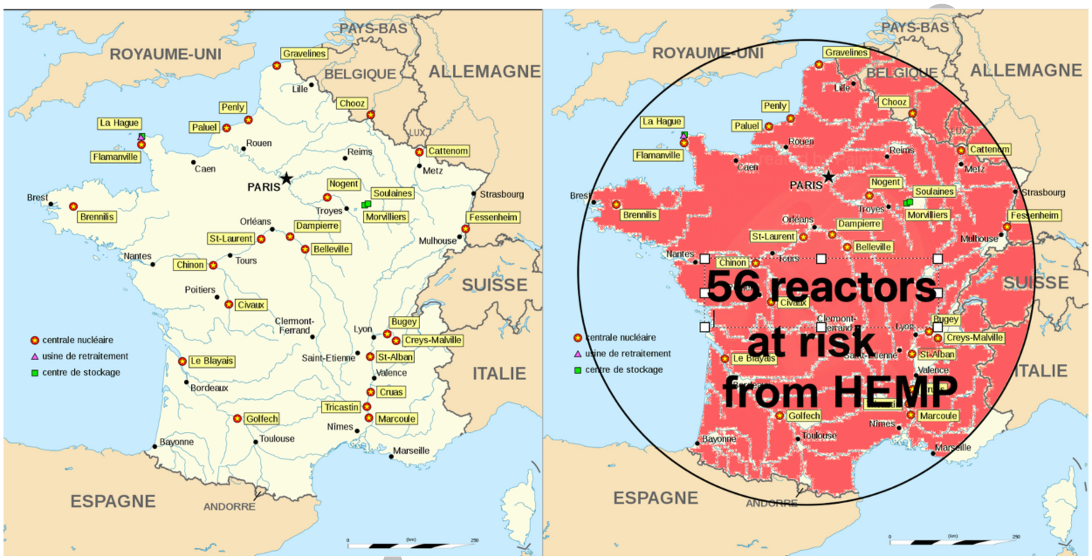


Figure 3: Fifty-six French nuclear reactors would be within the areas predicted to have HEMP E1 levels of 12,500 volts per meter or greater created by a single HEMP created by one 500-kiloton warhead detonated at an altitude of 75 km (42 miles).[27]

**Effects of HEMP on Spent Fuel Pools at Nuclear Power Plants**

Nuclear power plants require on-site spent fuel pools, which allow operators to safely remove used or "spent" uranium fuel rods from the reactor core during refueling operations (every 18 to 24 months) and place them into these pools. Spent fuel is highly radioactive; it must be kept constantly kept underwater during refueling and subsequent storage (5 years or longer) to shield people from its extremely lethal levels of radiation. The pools also actively cool the rods

[27] Map of French nuclear power plants from Wikimedia, by Eric Gaba – Wikimedia Commons user: Sting

because the radiation within the rods creates a huge amount of heat, which would cause the rods to ignite on contact with air and release huge amounts of radiation.

Nuclear power plants require off-site electric power (supplied by the national electric power grid) to continuously cool their spent fuel pools.[28] The pools each typically contain about 4 to 5 times more long-lived radioactive fission products than are found inside each reactor core.[29] These pools contain some of the highest concentrations of radioactivity on the planet, yet they are located *outside* of the primary containment vessel that houses the nuclear reactor,[30] which means they lack the "defense in depth" protection from a release of radiation that the primary containment affords the reactor core

Spent fuel pools each have large cooling systems that circulate water through the pools and remove the heat with heat exchange units. If HEMP eliminates all sources of electric power and/or disables the motor-driven cooling pumps in the cooling system, the spent fuel pools can only be cooled by pumping water into the pool.[31] If a spent fuel pool is not continuously cooled, then, in a matter of hours or days, the water in the pool will heat to the point of boiling.[32] The water in the pool will then "boil-off", exposing the spent fuel rods to steam and water.[33]



[28] Off-site power is also required to run the primary cooling pumps and to restart a nuclear power plant.

[29] "Spent fuel pools at nuclear reactors contain a substantially larger inventory of irradiated fuel than the reactors. Typical 1,000-megawatt PWR and BWR reactor cores contain about 80 metric tons and 155 metric tons respectively, while their pools typically contain 400 to 500 metric tons.9 About 40 percent of the total radioactivity in spent fuel (4.5 billion curies) for both designs is from cesium-137. This is about four to five times the amount of cesium-137 in their reactor cores." From Alvarez, R. (Winter 2012). "Improving Spent-Fuel Storage at Nuclear Reactors", Issues in Science and Technology, The National Academies of Sciences Engineering Medicine, p. 80. https://issues.org/alvarez/

[30] Macfarlane, A. (2017). "Risks of Densely Packed Spent Fuel Pools", Nautilus Institute for Security and Sustainability. https://nautilus.org/uncategorized/risks-of-densely-packed-spent-fuel-pools/

[31] The Emergency Diesel Generators are to provide power to cool the reactor core, but not the spent fuel pools. Wright, D. (March 27, 2011). Where Did the Water in the Spent Fuel Pools Go?", Union of Concerned Scientists. https://allthingsnuclear.org/dwright/where-did-the-water-in-the-spent-fuel-pools-go/

[32] M.D'Onorio, A. Maggiacomo, F. Giannetti, G. Caruso. (April 2022). "Analysis of Fukushima Daiichi unit 4 spent fuel pool using MELCOR", Journal of Physics Conference Series, DOI:10.1088/1742-6596/2177/1/012020

[33] The time to boil-off is a function of what percentage of spent fuel has been recently removed from the reactor core, as well as how much spent fuel has been loaded into the pool using high-density storage.

If the spent fuel are exposed to steam or air, the rods will heat to the point of rupture (and ignition, in the case of rods recently removed from the reactor core) and release *massive* amounts of radioactivity.[34] The radioactive fallout released by a single spent pool fire could easily leave *tens of thousands of square miles uninhabitable for centuries.*[35] [36] *Dozens of spent fuel pool fires – created by a single HEMP – could leave much of the U.S. uninhabitable for centuries.*

***Protect the U.S. National Electric Grid and Critical National Infrastructure from HEMP***

Technology exists that could effectively shield LPTs from both HEMP and GMD; if installed, it would protect the U.S. power grid and U.S. critical national infrastructure from destruction. There are a number of detailed technical papers that explain how this can be accomplished.[37] [38] [39] [40] [41] The estimated costs to protect the U.S. grid and infrastructure are in the tens of billions of dollars, which is a small fraction of what the U.S. spends each year on its defense budget and is less than a quarter of what the U.S. sent to Ukraine in 2022.



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[34] Alvarez, R. Beyea, J. Janberg, K. Kang, J. Lyman, E. Macfarlane, A. Thompson, G. von Hippel, F. (2003). "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States", Science and Global Security, 11:1–51. https://scienceandglobalsecurity.org/archive/sgs11alvarez.pdf

[35] Op. cit. "Electromagnetic Defense Task Force (EDTF) Report 2.0, LeMay Paper No. 4", page 13.

[36] Op. cit. "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States"

[37] Kappenman, J. (January 2010), "Low-Frequency Protection Concepts for the Electric Power Grid: Geomagnetically Induced Current (GIC) and E3 HEMP Mitigation", Metatech Corporation, Meta-R-322. https://www.ferc.gov/sites/default/files/2020-05/ferc_meta-r-322.pdf

[38] The Foundation for Resilient Societies. (September 2020) "Estimating the Cost of Protecting the US Electric Grid from Electromagnetic Pulse. https://www.resilientsocieties.org/uploads/5/4/0/0/54008795/estimating_the_cost_of_protecting_the_u.s._electric_grid_from_electromagnetic_pulse.pdf

[39] International Electrotechnical Commission. (May 17, 2017). "Electromagnetic compatibility (EMC) - Part 5-10: Installation and mitigation guidelines - Guidance on the protection of facilities against HEMP and IEMI https://standards.iteh.ai/catalog/standards/iec/b66818ad-403e-47ec-98bb-ba156e7cb367/iec-ts-61000-5-10-2017

[40] Op. cit. Radasky, "Protecting Industry from HEMP and IEMI"

[41] Radasky, W., Savage, E. (Jan 2010). "High-Frequency Protection Concepts for the Electric Power Grid", Metatech Corp, Meta-R-324. https://www.ferc.gov/sites/default/files/2020-05/ferc_meta-r-324.pdf

***Protect U.S. Nuclear Power Plants and Spent Fuel Pools from HEMP***

Technology exists that could effectively shield the solid-state electronics and integrated circuits in the emergency power systems and Emergency Core Cooling Systems at U.S. nuclear power plants. Retrofitting nuclear power plants to protect them from HEMP could greatly reduce and possibly eliminate the risk of reactor meltdowns, as well as boil-offs of the spent fuel pools. There are experts and technical papers that explain how this can be accomplished.[42] [43] [44]

Because spent fuel must be isolated from the biosphere *for at least 100,000 years*, it is unrealistic to assume it can be monitored for that length of time. There is no current long-term technical solution to high-level nuclear waste storage that is without serious concerns. Proposed geological underground permanent storage solutions have major unresolved technical problems. No nuclear waste containers exist that can withstand the harsh environment that will exist in underground facilities for thousands of centuries. It appears the long-term solution to its storage – geologic underground storage versus storage on the Earth's surface with an almost infinite stewardship (in human terms) – is still a matter of debate.

Unfortunately, the Nuclear Regulatory Commission has refused to recognize the dangers posed by HEMP to nuclear power plants, and the nuclear utilities have to date resisted all efforts to retrofit nuclear power plants with technology that would shield against the effects of HEMP. Consequently, no steps have been taken to install equipment and modifications that would protect U.S. nuclear power plants from HEMP (and this is the situation in many other nations).



[42] International Electrotechnical Commission. (17-May-2017). "Electromagnetic compatibility (EMC) - Part 5-10: Installation and mitigation guidelines - Guidance on the protection of facilities against HEMP and IEMI https://standards.iteh.ai/catalog/standards/iec/b66818ad-403e-47ec-98bb-ba156e7cb367/iec-ts-61000-5-10-2017
[43] Op. cit. Radasky, "Protecting Industry from HEMP and IEMI"
[44] Radasky, W., Savage, E. (Jan 2010). "High-Frequency Protection Concepts for the Electric Power Grid", Metatech Corp, Meta-R-324. https://www.ferc.gov/sites/default/files/2020-05/ferc_meta-r-324.pdf

American citizens, along with many other people in the world, remain very much at risk from the catastrophic effects of HEMP (and GMD).[45]



[45] Op. cit. "Low-Frequency Protection Concepts for the Electric Power Grid".