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

By Steven Starr

This paper describes the effects of nuclear weapons that produce a maximum HEMP E1 incident energy of 50 kV/M – about one-quarter to one-half of the incident energy fields produced by the "Super-EMP" weapon described in Russian[1] and Chinese[2] military sources. Russian open-source military writings claim that Super-EMP weapons generate such powerful fields that even hardened U.S. strategic forces would be vulnerable.[3] If Super-EMP weapons are used in an attack against the US, the effects of HEMP could be significantly more severe than those described in this paper. Extreme cold and hot weather conditions would also increase the damage caused by HEMP.

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[1] Vaschenko, A. (November 1, 2006). "Russia: Nuclear Response to America Is Possible Using Super-EMP Factor", "A Nuclear Response To America Is Possible," Zavtra,

[2] Zhao Meng, Da Xinyu, and Zhang Yapu, (May 1, 2014). "Overview of Electromagnetic Pulse Weapons and Protection Techniques Against Them" Winged Missiles (PRC Air Force Engineering University.

[3] Vaschenko, A., Belous, V. (April 13, 2007); "Preparing for the Second Coming of 'Star Wars", *Nezavisimoye Voyennoye Obozreniye* translated in *Russian Considers Missile Defense Response Options* CEP20070413330003.

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Executive Summary

A nuclear weapon detonated in the upper atmosphere will produce a High-altitude Electromagnetic Pulse (HEMP).[4] 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 can induce highly destructive transient electric voltages and currents into any electrically conductive material located in the affected regions. A primary concern is that HEMP will induce high voltages and currents into overhead power transmission lines, telecom lines, and cables, which will subsequently damage or destroy a significant portion of any unshielded electronic equipment connected to these lines.

The destructive effects from a single HEMP on Large Power Transformers and high-speed circuit breakers could easily bring down most or all of the U.S. national electric grid for many months or even a year or longer. HEMP will also render inoperable much of the U.S. critical national infrastructure through the destruction of the integrated circuits (microchips, microprocessors, logic circuits) that are found within almost all modern electronic devices.

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.[5] These high voltages and currents will destroy

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

[5] 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

tens of millions of insulators on power distribution lines.[6] The failure of a single insulator on a power distribution line can result in the loss of the whole line.[7] 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").[8] LPTs make up less than 3% of transformers in U.S. power substations, but they carry 60%-70% of the nation's electricity.[9]

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"*[10] (this is also true for an extreme Geomagnetic Disturbance or GMD,[11] which has quite similar effects to those created by the E3 component of HEMP). A single HEMP would likely damage or destroy the majority of LPTs in an entire geographic region.

Thus, one HEMP (or massive GMD) would immediately leave entire regions of the U.S. without electric power – and some regions would remain without power for months or years. This is because (1) it will take a long time to replace many millions of insulators on power

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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.
[6] Personal correspondence with Dr. William Radasky, January 9, 2022.
[7] Savage, E., Gilbert, J., Radasky, W. (January 2010). "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", Metatech Corporation, Meta-R-320, p. 7-3. http://www.futurescience.com/emp/ferc_Meta-R-320.pdf
[8] 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
[9] 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.
[10] Ibid, p. 3-2
[11] 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. For detailed analysis, see Kappenman, J. (January 2010). "Geomagnetic Storms and Their Impacts of the U.S. Power Grid", Metatech Corporation, Prepared for Sandia National Laboratories. https://www.futurescience.com/emp/ferc_Meta-R-319.pdf

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,[12] however, it might prove to be impossible to domestically manufacture LPTs if all or most of the U.S. national electric grid was down for months or longer; replacement LPTs would have to be imported if they had not been stockpiled. The same is true for manufacturing and replacing millions of insulators on power distribution lines.

Prior to 2020, the U.S. had to import 82% of its LPTs.[13] The lead time for LPTs manufactured overseas is currently 12 to 18 months.[14] LPTs weigh between 100 to 400 tons;[15] imported LPTs must be shipped by sea freight (too heavy for air freight), which extends shipping times.[16] 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 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

The E1 component of HEMP can also disable, damage, or destroy any unprotected solid-state electronics and integrated circuits within the modern electronic equipment that is essential

[12] 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/
[13] 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
[14] 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
[15] 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
[16] Op. cit. "Transformative Times: Update on the US.S. Transformer Supply Chain"

to the operations of critical national infrastructure.[17] Throughout large geographic regions, HEMP would not only stop the delivery of electric power, it would also wreck the integrated circuits *within* the electronic equipment required to operate:

- 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

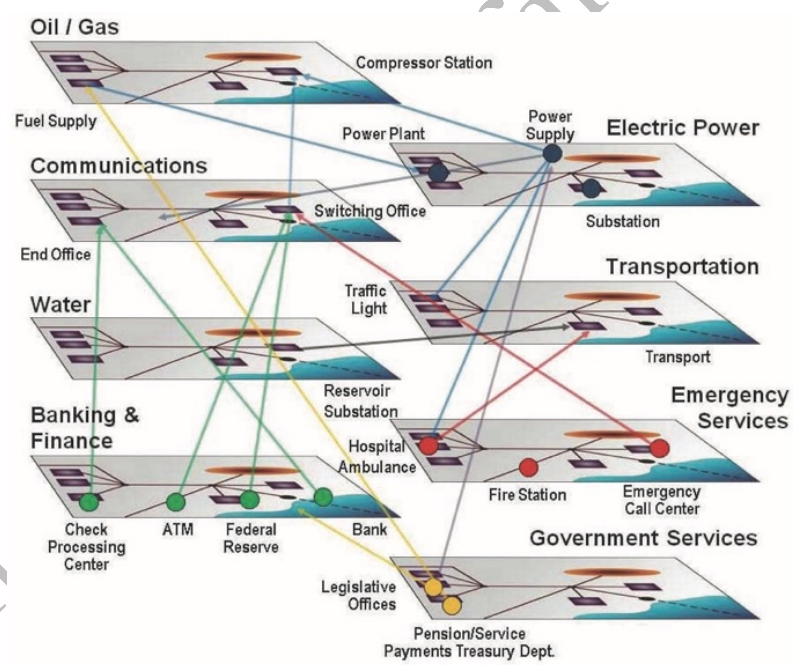

Figure 1: A Conceptual Illustration of the Interconnectedness of Elements Contained Within Each Critical Infrastructure. Some connections are not shown (diagram originally from Sandia National Laboratory).[18]

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 found within the electronic devices

[17] 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/

[18] 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

required by these systems (assuming replacement parts were available) before most critical national infrastructure could resume normal operations.

Without electric power from the grid, US 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. In other words, a single HEMP (or massive GMD) could now create a 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).[19]

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

Technology exists that could effectively protect the LPTs from both HEMP and GMD; if installed, it would protect the US power grid from destruction. Likewise, the vulnerable components in US national infrastructure can also be shielded to a significant degree from HEMP (this also holds true for the controls and circuits in the cooling systems and backup power

[19] 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."

systems at nuclear reactors). There are a number of detailed technical papers that explain how this can be accomplished.[20] [21] [22] [23] [24]

Findings of the 2008 Congressional EMP Commission have led some experts to state that the LPT's and electronic control systems in the national electric grid could be protected from natural and manmade EMP (including HEMP and non-nuclear Intentional Electromagnetic Interference devices[25]) for about $2 billion, with implementation, on a non-emergency basis, that would require 3-5 years.[26] Another organization estimated (in 2020) that all national critical infrastructures could be protected for $10 billion to $30 billion dollars.[27] (Note that some critics from the electric utility companies dispute these estimates.[28]) Legislation was drafted in 2013 (the Secure High-Voltage Infrastructure for Electricity From Lethal Damage Act, or the SHIELD Act) and in 2015 (the Critical Infrastructure Protection Act, or CIPA) that would have mandated this protection. However, lobbying by the electric power industry prevented these bills from coming to a vote and killed the legislation.[29] All the various cost estimates to add this protection

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[20] 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

[21] 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

[22] 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

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

[24] 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

[25] Electric Infrastructure Security Council, "IEMI – Intentional Electromagnetic Interference", Retrieved Jan 2022 from https://eiscouncil.org/iemi-intentional-electromagnetic-interference/

[26] Secure the Grid Coalition, "EMP: Technology's Worst Nightmare". Retrieved Jan 2022 from https://securethegrid.com/emp-technologys-worst-nightmare/

[27] Op cit. "Estimating the Cost of Protecting the US Electric Grid from Electromagnetic Pulse".

[28] Edison Electric Institute, "Electromagnetic Pulses (EMPs): Myth vs. Facts". Retrieved Jan 07, 2022 from https://inldigitallibrary.inl.gov/sites/STI/STI/INL-EXT-15-35582.pdf

[29] American Leadership and Policy Foundation, (June 2015). "Electromagnetic Pulse and Space Weather and the Strategic Threat to America's Nuclear Power Stations", p. 38. Retrieved from https://www.itstactical.com/wp-

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.

However, the regulatory agencies for both the electrical and nuclear utilities have to date *resisted* all efforts to install such protective devices, primarily because of the cost involved. No significant steps have yet been taken to install equipment and modifications that would protect the U.S. national electric grid and U.S. critical national infrastructure from HEMP (and this is the situation in many other nations). Thus, American citizens, and many other people around the world, remain very much at risk from the catastrophic effects of HEMP (and GMD).[30]

content/uploads/2016/08/The-Strategic-Vulnerabilities-of-Nuclear-Plants-to-EMP-and-Solar-Events-ALPF-Final-24-Jan.pdf

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

How HEMP Can Destroy the Grid and Modern Electronic Devices

HEMP is created by a nuclear detonation that occurs above the Earth's lower atmosphere, beginning at an altitude of approximately 30 km (about 19 miles).[31] HEMP is a very complex phenomenon, which is made up of three successive energy waves: E1, E2, and E3, with HEMP E1 and E3 considered to be the most dangerous (Figure 2). The electromagnetic fields generated by HEMP can cover vast areas of land, as its energy waves follow a line-of-sight path from the burst point of the nuclear detonation out to the Earth's horizon. In general, the higher the point of detonation, the larger the area covered. However, the distribution of the energy fields created by E1 and E3 (the two most damaging forms of HEMP) are distinctly different and are maximized at different altitudes, so they must be considered on an individual basis.[32]

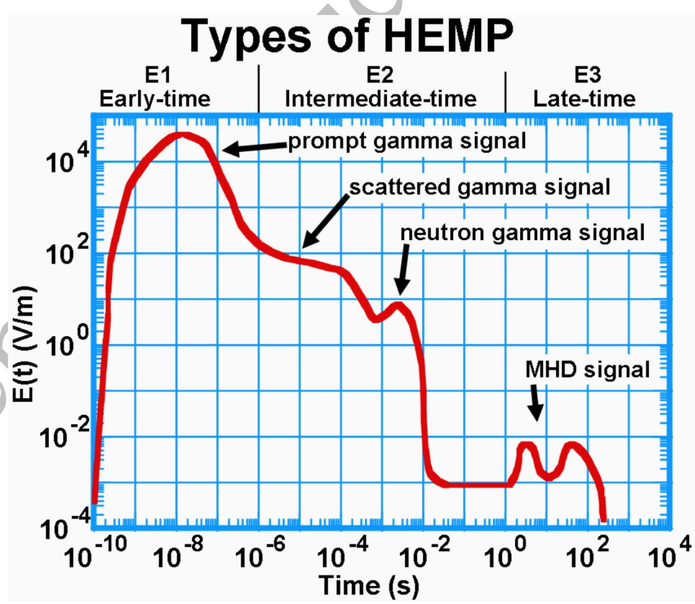

Figure 2: The Various Parts of a Generic HEMP.
The left column illustrates the Electrical energy of E1 in Volts per meter (V/m).[33]
Total Volts per meter produced by super-EMP weapons may be 2 to 4 times greater in magnitude than those produced by the nuclear weapons used in the calculations described in this paper.

[31] Op. Cit. "High-Frequency Protection Concepts for the Electric Power Grid", p. 2-1.
[32] Op. Cit. "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-1
[33] Op. Cit. ""High-Frequency Protection Concepts for the Electric Power Grid", p. 2-1.

A primary issue is that power lines, communication lines, and cables act as antennas to conduct EMP energy to unshielded equipment. HEMP pulses could damage or disrupt a significant portion of the equipment connected to power or data lines if the connections between the cables and the equipment are unprotected.

HEMP E3: Deadly Threat to the U.S. National Electric Grid

E3 follows E2 and is a much longer-lasting pulse than either E1 or E2. E3 HEMP is also called Magneto-hydrodynamic or MHD EMP as it arises from the motion of the ionized bomb debris and atmosphere relative to the geomagnetic field.[34] Unlike E1 and E2, which essentially act above ground level, E3 will also induce powerful current flows *well below ground level* into buried communication and power transmission lines.[35] E3 acts in a very similar manner to the destructive Geomagnetically Induced Current produced during a geomagnetic storm, although a nuclear E3 pulse can be significantly more intense than a solar storm induced GMD pulse.[36]

E3 primarily damages high voltage equipment connected to long-distance electric transmission lines, especially high-speed circuit breakers and Large Power Transformers (LPTs) over 100,000 volts (100 kV). LPTs are an absolutely essential part of the national electric grid; they are required for the long-distance transmission of electric power. LPTs convert or "transform" voltage into a required voltage, which may be stepped up to higher voltages or

[34] Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-1.
[35] Op. cit. "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-18. & Emanuelson, J. (July 7, 2019). "Soviet Test 184: The Soviet 1962 EMP Test over Kazakhstan". https://www.futurescience.com/emp/test184.html
[36] "Geomagnetic storm and E3 HEMP environments can develop almost instantaneously over large geographic footprints, which have the ability to essentially blanket the continent with an intense threat environment and have the capability to produce significant collateral damage to critical infrastructures . . . no comprehensive design criteria have ever been considered to check the impact of the geomagnetic storm environment.", Op. Cit. "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", pp. 2-46, 2-47.

stepped down to lower voltages. According to the Energy Department's Office of Electricity, over 90 percent of the electricity consumed in the U.S. passes through LPTs.[37]

The destruction of LPTs would eliminate the ability for electrical power to be transmitted from the Generating Stations to end users. Figure 3 illustrates the critical role played by LPTs in the US national power grid. The Step-Up and Step-Down transformers that are circled in red are the LPTs at most risk.

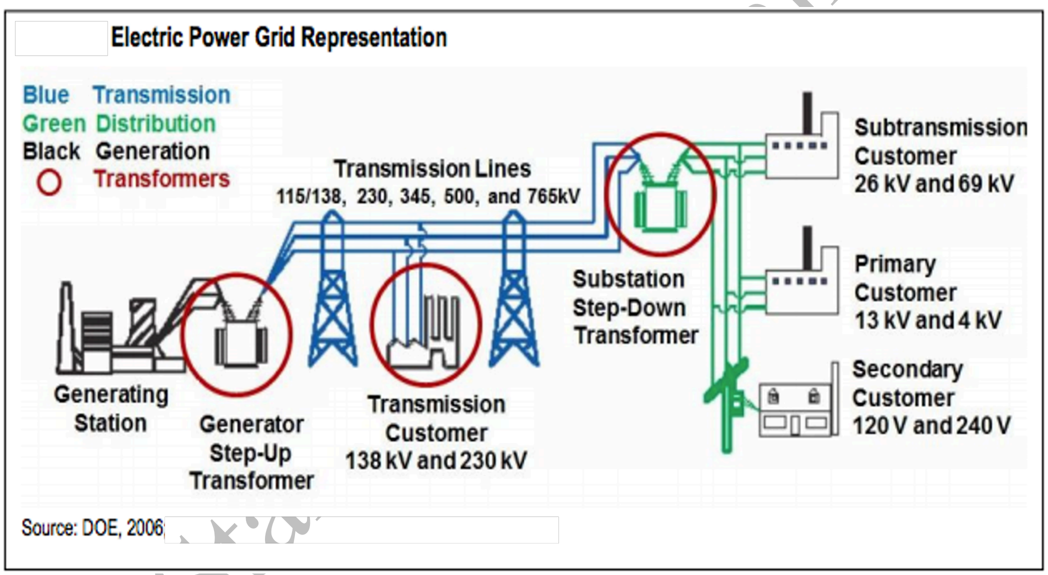

Figure 3: Large Power Transformers (LPTs) circled in red. LPTs are essential for the US national power grid to operate.[38]

E3 can disable, damage, and destroy the 345 kV, 500 kV, and 765 kV LPTs that populate the grid, which, if left unshielded, all are extremely susceptible to E3 and GMD.[39] Should many or most of these LPTs be put out of operation, much or all of the US national electric grid would be put out of service. There are approximately 1800 major transmission lines of 345 kV or higher

[37] Op. cit. "Transformative Times: Update on the U.S. Transformer Supply Chain
[38] U.S.-Canada Power System Outage Task Force. (April 2004). "U.S.-Canada Power System Outage Task Force, Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations", Figure 2.1, p. 5. https://www.energy.gov/sites/default/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf
[39] Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-32.

operating voltage, and about 5000 circuit breakers of 345 kV or higher operating voltage across the contiguous United States (Figure 4);[40] most, if not all of these would be knocked out of commission by the combined effects of HEMP. Figure 5 illustrates the number and percentages of LPTs used in the U.S. national electric grid.

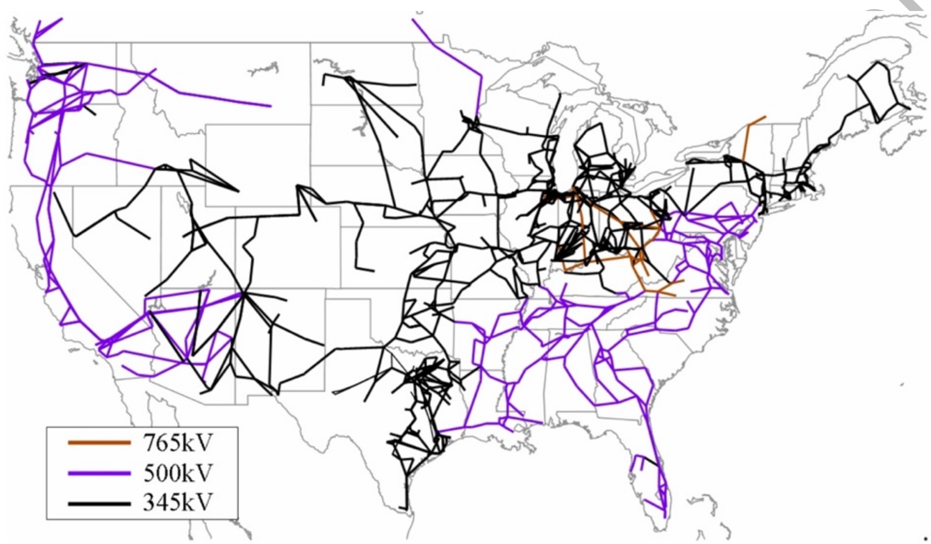

Figure 4: U.S. High-Voltage Transmission Lines[41]

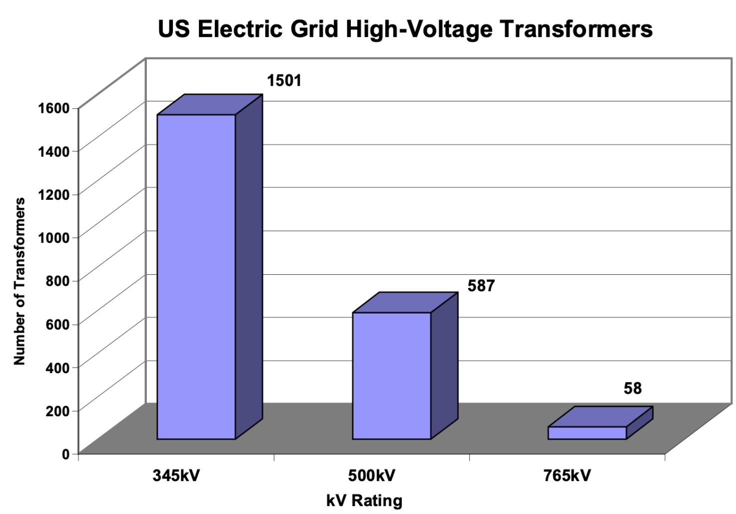

Figure 5: Large Power Transformers (LPTs) in the U.S. national electric grid.[42]

[40] Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 4-2.
[41] Ibid, p. 2-31.
[42] Ibid, p. 2-32.

The US electrical power grid, which supports all the other critical infrastructures, is already extremely fragile and vulnerable to any EMP attack.[43] The average age of installed LPTs in the United States is about 38 to 40 years, with 70 percent of LPTs being 25 years or older.[44] There are only 8 companies in the U.S. currently manufacturing LPTs[45] and there is only one U.S. company that manufactures the Grain-Oriented Electrical Steel required to make the cores and laminations inside LPTs.[46] A heavily redacted report published in 2020 by the Department of Commerce stated:

> "*Of particular concern is lack of domestic capacity with regard to extra high voltage transformers (those with >345 kV voltage rating) that are vital for long distance electricity transmission. This excessive level of foreign dependence on imported LPT, which are uniquely critical to the U.S. Bulk Power System puts the resiliency of the critical energy infrastructure at risk.*"[47]

The current lead time for domestic production of LPTs is 38 months,[48] however, it would probably be impossible to domestically manufacture LPTs if all or most of the US national electric grid was down for months or longer. The lead time for LPTs manufactured overseas is currently 12 to 18 months.[49] LPTs typically weigh 670,000 to 820,000 pounds; the heaviest load

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[43] Radasky, W., Pry, P. (July 6, 2010). "Rebuttal to "The EMP threat: fact, fiction, and response", The Space Review in association with Space News. https://www.thespacereview.com/article/1656/1

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

[45] Op. cit. "How a transformer shortage threatens the grid"

[46] U.S. Department of Commerce. (October 15, 2020). "The Effect of Imports of Transformers and Transformer Components on the National Security, Final Report", Bureau of Industry and Security , Office of Technology Evaluation, p. 9. https://www.bis.doc.gov/index.php/documents/section-232-investigations/2790-redacted-goes-report-20210723-ab-redacted/file

[47] Op. cit. "The Effect of Imports of Transformers and Transformer Components on the National Security, Final Report", p. 233.

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

[49] Op. cit. Inaction on electric transformer crisis adds reliability concerns, APPA warns"

a railroad car typically carries is 200,000 pounds (Figure 6).[50] Imported LPTs must be shipped by sea freight (too heavy for air freight), which extends shipping times.[51] Even if the national electric grid was functional , it would be a logistical nightmare to move more than one thousand replacement LPTs following a HEMP (or GMD). This might prove an almost impossible task in a situation where the grid had been down for many months.

Figure 6: Workers move wires, lights, and poles to transport a 340-ton LPT, causing hours of traffic delay. LPTs can weigh up to 400 tons, four times more than rail transport can handle.[52]

E3A Blast Wave and E3B Heave Wave

E3 consists of two distinct waves: E3A followed by E3B. They occur at two distinct times and the electrical fields they create have two distinctively different geographical distributions.[53] Both E3A and E3B pose a grave threat to the LPTs and their circuit breakers and relays, which are required to distribute electricity throughout the U.S. national electric power

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[50] U.S. Department of Energy, Infrastructure Security and Energy Restoration Office of Electricity Delivery and Energy Reliability (April 2014) "Large Power Transformers and the US Electric Grid", p. vi. https://www.energy.gov/sites/prod/files/2014/04/f15/LPTStudyUpdate-040914.pdf
[51] Op. cit. "Transformative Times: Update on the US.S. Transformer Supply Chain"
[52] Op. cit. "Large Power Transformers and the U.S. Electric Grid", p. vi
[53] Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 1-3.

grid (the same holds true for similar unshielded equipment required for other national power grids).

The E3A Blast Wave occurs during a 1 to 10 second interval and consists of a geomagnetic field produced by the expansion of the fireball, which is most likely to effect large power lines. E3A effects are most pronounced at night and its most intense effects are experienced far north of where the detonation occurs. The higher the detonation and the larger the weapon, the larger are the effects (maximum E3A Blast Wave effects occur at an altitude of about 400 km/259 miles).[54] E3A has a shorter duration than E3B but it produces a more intense geomagnetic field disturbance. *The E3A from a single HEMP detonation can bring down the entire U.S. electric grid* (see Figure 7),[55] however, it appears that the point of detonation would have to be located very far south of the U.S. (over southern Mexico, see Figure 9).[56]

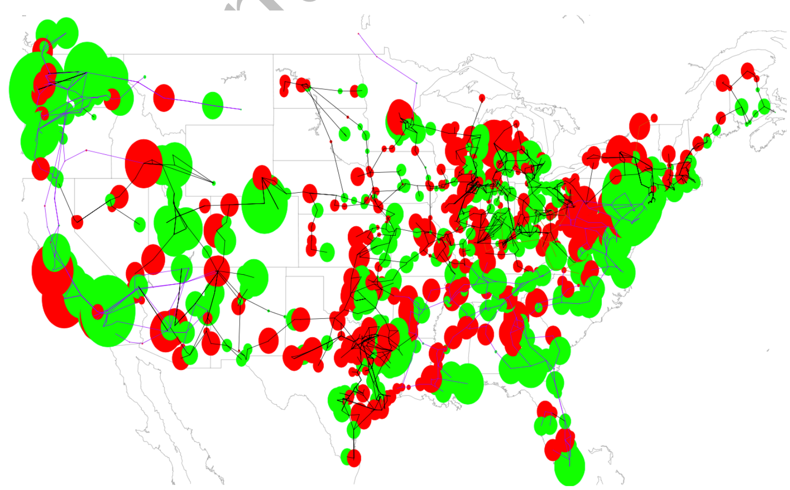

Figure 7: Summary of GIC flows in U.S. power grid for E3A Blast Wave Case B17a. The entire U.S. Power Grid is expected to collapse.[57]

[54] Ibid, p. 2-14.
[55] Ibid, p. 3-2.
[56] Thus, it may more likely that the E3B wave would be employed by war planners, as the effects of E3B are more centralized beneath the point of nuclear detonation, as are the effects of E1, so they could be combined. The optimum altitude would be somewhere around 100 to 130 km.
[57] Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 4-2.

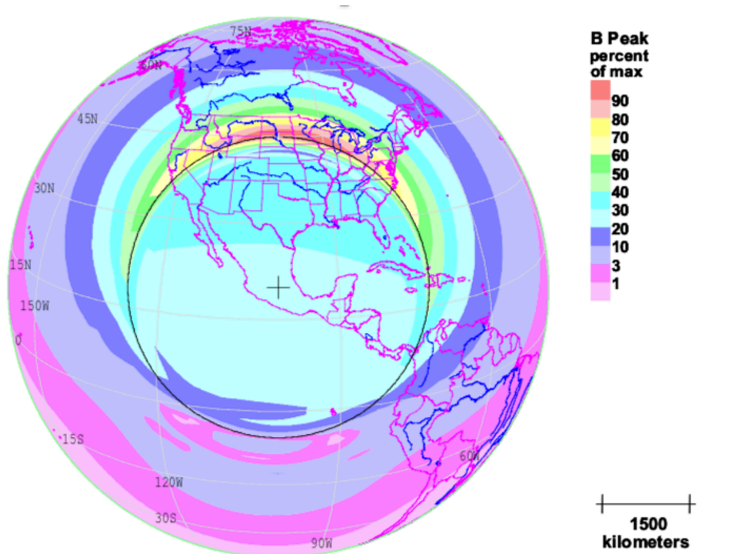

Figure 8: HEMP E3A Blast Wave, the initial component of HEMP E3, burst height 500 km[58]

The E3B Heave Wave follows E3A and occurs during a 10 to 300 second interval. E3B is created by the heated debris ionizing the upper atmosphere while crossing geomagnetic lines that produce currents and magnetic fields beneath it on the surface of the Earth.[59] E3B works by inducing electric currents and magnetic fields into the Earth, which then produce magnetic fields on (or near) the surface of the earth. This will act to induce current into both buried and above ground conductors (especially power lines and phone lines).

In contrast to the E3A Blast Wave, the most damaging effects from E3B Heave Wave occur at much lower burst altitudes. E3B Blast Wave is generally distributed around the point of the nuclear detonation; its most intense electrical fields are created at a burst height of 130 km (Figure 9) and 300 km (Figure 10).[60]

[58] Ibid, p. 2-4
[59] Ibid, pp. 2-8 and 2-9.
[60] Unlike the E3A Blast Wave, the E3B peak electric field "saturates below a 100-kiloton yield, and larger devices do not produce a higher field, although the pattern enlarges for larger yields, creating a larger region on the ground where the horizontal electric field is near its peak value." Ibid, p. 2-15.

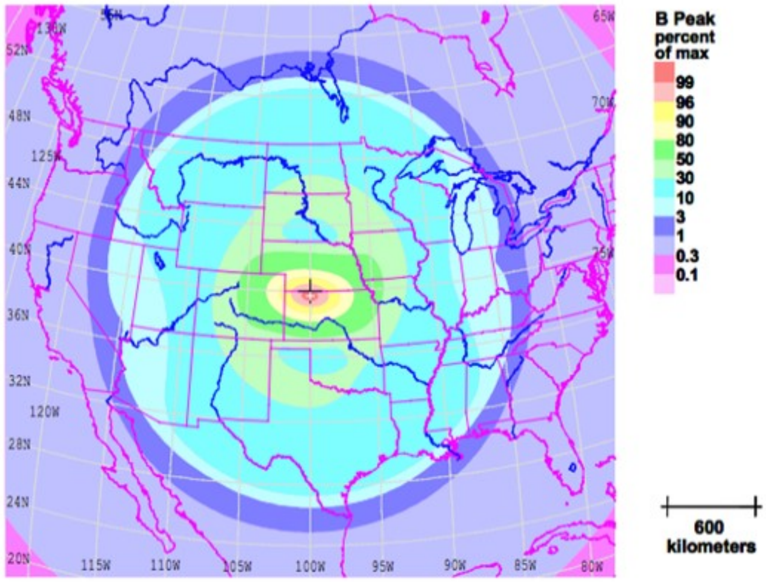

Figure 9: HEMP E3B Heave Wave, height of detonation 130 km, yield unspecified.[61]

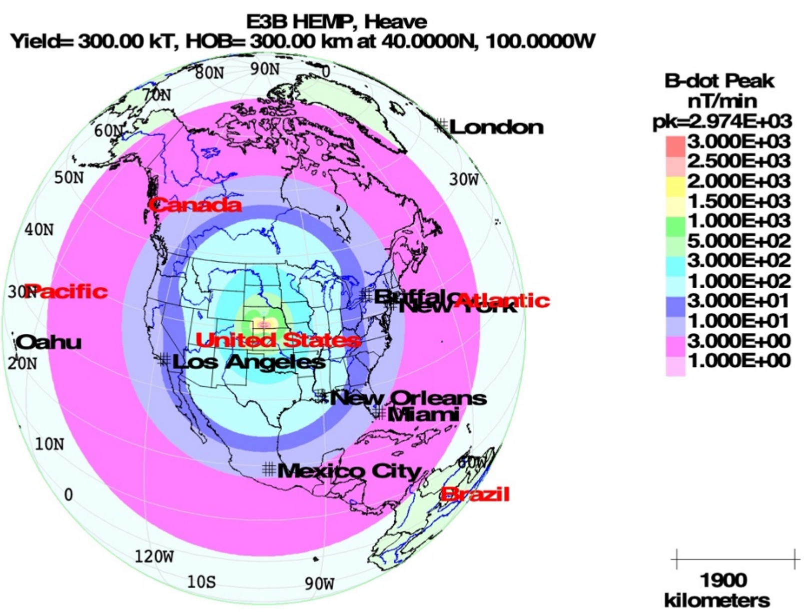

Figure 10: Magnetic Field Peak Contour Pattern from E3B, from 300-kiloton burst at 300 km height[62]

[61] Ibid, p. 2-12

[62] National Coordinating Center for Communications. (Feb 5, 2019). "Electromagnetic Pulse (EMP) Protection and Resilience Guidelines for Critical Infrastructure and Equipment", Version 2.2, National Cybersecurity and Communications Integration Center, Arlington, Virginia, p. 10. https://www.cisa.gov/sites/default/files/publications/19_0307_CISA_EMP-Protection-Resilience-Guidelines.pdf

The maximum field strength for E3B is developed in the regions directly below the detonation where the atmosphere is most intensely heated.[63] *The E3B from a single HEMP can bring down the electric grid over an entire geographic region such as the Eastern and Southeastern U.S.* (Figure 11) *or the West Coast of the U.S.* (Figure 12).[64]

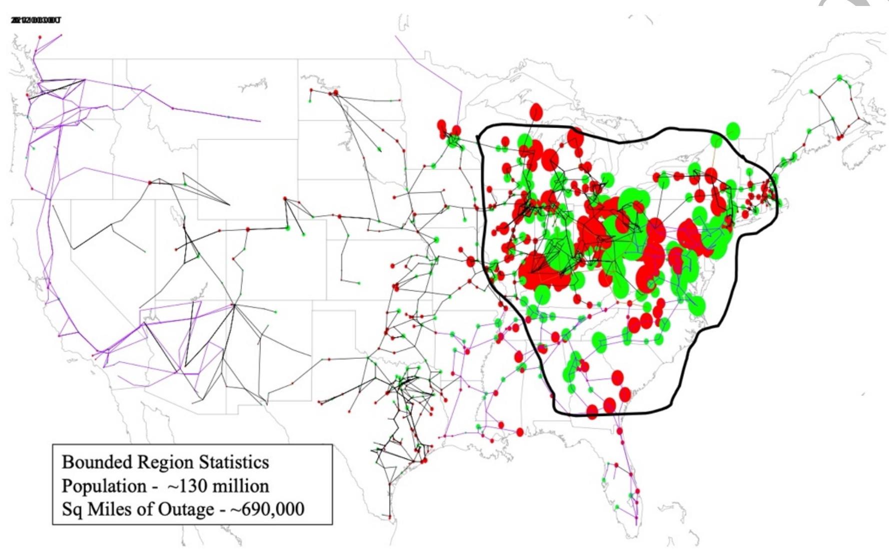

Figure 11: E3B over Columbus, Ohio collapses the grid in circled region[65]

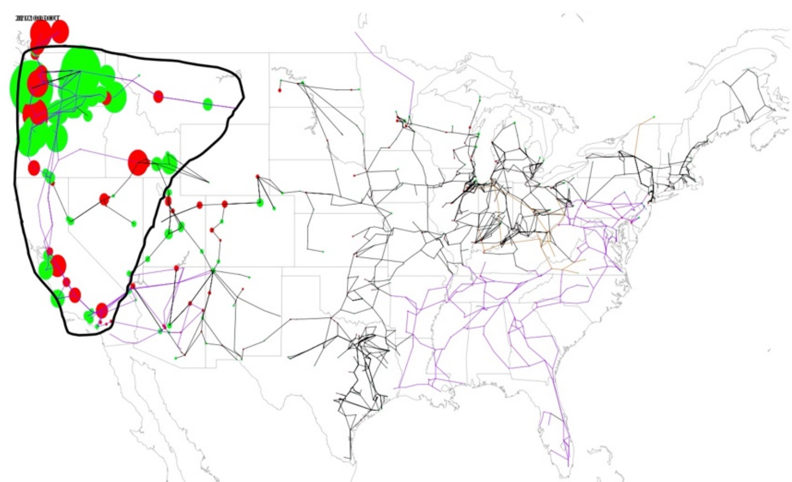

Figure 12: E3B over Portland, Oregon collapses the grid in circled region[66]

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[63] Ibid, p. 2-11.
[64] Ibid, pp. 3-5 through 3-12.
[65]Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 3-5.
[66] Ibid, p. 3-11.

E3: Summary of effects

Both E3A and E3B will induce large, damaging currents into electric power transmission lines and buried transmission lines.[67] This will cause near-simultaneous, multipoint failures in power system infrastructures and includes the widespread destruction of Large Power Transformers (LPTs).[68] The U.S. national power grid absolutely requires LPTs for the long-distance transmission of electricity, so *any significant loss of LPTs could bring down much or all of the U.S. national electric grid.*[69] The large generator Step-Up transformers that are used at nuclear power plants are also highly susceptible to E3 (and GMD), and the catastrophic failure of GSUs could cause failure of control and safety systems at nuclear power plants.[70]

Scientists have confirmed, by "*all means of measurement*", that the threat potential posed by HEMP exceeds the intended stress limit that the US power network is designed and tested to withstand[71] (this is also true for an extreme Geomagnetic Disturbance or GMD[72]). A single HEMP would likely destroy or damage the majority of LPTs in the U.S. electric power grid, leaving most U.S. citizens without electricity for a period of months or years. A HEMP

[67] Ibid, page 2-18

[68] Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", pp. 2-46 and 2-47. There would be little or no time for meaningful human interventions in such circumstances.

[69] Most electricity is transmitted at 115 to 765 vK for low-loss, long-distance transmission, and the LPTs are required for this. U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability. (April 2014). "Large Power Transformers and the U.S. Electric Grid". https://www.energy.gov/sites/prod/files/2014/04/f15/LPTStudyUpdate-040914.pdf

[70] Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 5-1 and 5-2.

[71] Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 3-2

[72] 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. For detailed analysis, see Kappenman, J. (January 2010). "Geomagnetic Storms and Their Impacts of the U.S. Power Grid", Metatech Corporation, Prepared for Sandia National Laboratories. https://www.futurescience.com/emp/ferc_Meta-R-319.pdf

experienced during extreme cold and hot weather conditions would also increase the damage caused by HEMP.[73]

Preventative Measures to Protect the National Grid

Technology exists that could effectively protect the LPTs from both HEMP and GMD; if installed, it would protect the US power grid from destruction. There are a number of detailed technical papers that explain how this can be accomplished.[74] [75] [76] [77] [78] Findings of the 2008 Congressional EMP Commission have led some experts to state that the LPT's and electronic control systems in the national electric grid could be protected from natural and manmade EMP (including HEMP and non-nuclear Intentional Electromagnetic Interference devices[79]) for about $2 billion, with implementation, on a non-emergency basis, that would require 3-5 years.[80] Another organization estimated (in 2020) that all national critical infrastructures could be protected for $10 billion to $30 billion dollars.[81] (Note that some critics from the electric utility companies dispute these estimates.[82]) Legislation was drafted in 2013 (the Secure High-Voltage

[73] Op. cit., "The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", pp. 3-1, 3-2.
[74] 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
[75] The Foundation for Resilient Societies, "Estimating the Cost of Protecting the US Electric Grid from Electromagnetic Pulse, September 2020. https://www.resilientsocieties.org/uploads/5/4/0/0/54008795/estimating_the_cost_of_protecting_the_u.s._electric_grid_from_electromagnetic_pulse.pdf
[76] 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
[77] Op. cit. Radasky, "Protecting Industry from HEMP and IEMI"
[78] Op. cit. "High-Frequency Protection Concepts for the Electric Power Grid"
[79] Electric Infrastructure Security Council, "IEMI – Intentional Electromagnetic Interference", https://eiscouncil.org/iemi-intentional-electromagnetic-interference/
[80] Secure the Grid Coalition, (Jan 12, 2023). "EMP: Technology's Worst Nightmare". https://securethegrid.com/emp-technologys-worst-nightmare/
[81] Op cit. "Estimating the Cost of Protecting the US Electric Grid from Electromagnetic Pulse".
[82] Edison Electric Institute, (Jan 2016). "Electromagnetic Pulses (EMPs): Myth vs. Facts". https://inldigitallibrary.inl.gov/sites/STI/STI/INL-EXT-15-35582.pdf

Infrastructure for Electricity From Lethal Damage Act, or the SHIELD Act) and in 2015 (the Critical Infrastructure Protection Act, or CIPA) that would have mandated this protection. However, lobbying by the electric power industry prevented these bills from coming to a vote and killed the legislation.[83]

In March 2017, the Assistant Secretary of the Department of Energy instructed the Electric Reliability Organization,[84]and owners of critical electric infrastructure and defense and military installations, to

> *". . . prepare and submit to Congress a plan to establish a Strategic Transformer Reserve for the storage, in strategically located facilities, of spare large power transformers and emergency mobile substations in sufficient numbers to temporarily replace critically damaged large power transformers and substations that are critical electric infrastructure or serve defense and military installations."*[85]

Unfortunately, no Strategic Transformer Reserve has been created, although a new design for a "Flexible Transformer" has been successfully developed by General Electric Renewable Energy's Grid Solutions unit.[86] A unit with variable settings, ranging from 69kV to 161kV, has been built and tested;[87] GE engineers are currently working on designs for the LPTs.

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[83] American Leadership and Policy Foundation, (June 2015). "Electromagnetic Pulse and Space Weather and the Strategic Threat to America's Nuclear Power Stations", p. 38. https://www.itstactical.com/wp-content/uploads/2016/08/The-Strategic-Vulnerabilities-of-Nuclear-Plants-to-EMP-and-Solar-Events-ALPF-Final-24-Jan.pdf

[84] An organization that has been certified by the Federal Energy Regulatory Commission (FERC) to establish and enforce reliability standards for the US bulk power system.

[85] U.S. Department of Energy. (March 2017). "Strategic Transformer Reserve", Report to Congress. https://www.energy.gov/sites/prod/files/2017/04/f34/Strategic%20Transformer%20Reserve%20Report%20-%20FINAL.pdf

[86] Kellner, T. (October 27, 2021). "Special Power: 'Flexible Transformer' Could Become the Grid's New Superhero", https://www.ge.com/news/reports/special-power-flexible-transformer-could-become-the-grids-new-superhero

[87] Personal communication with John Gilbertson of Cooperative Energy of Hattiesburg, Mississippi Jan 19, 2023.

However, the opposition from electric utilities and lack of interest from the Biden administration has currently resulted in no Federal legislation mandating comprehensive action to protect LPTs from HEMP/EMP. This leaves the U.S. national electric grid – and the American public – at extreme risk from HEMP.

HEMP E2: Effects Similar to Those Produced by Lightning

E2 follows E1 and E2 lasts only one or two seconds. E2 is similar to lightning and can inflict a similar level of damaging energy, but it is of less concern than E1 or E3 because most electronic systems have some protection against E2.[88] However, E1 may damage or disable electronic systems including surge protection systems that protect against E2, leaving them vulnerable to the effects of the E2 and E3 waves that follow. The specialized devices and techniques that protect against E1 will help protect against E2.[89]

HEMP E1: Threat to Modern Electronics and Insulators on Powerlines

E1 is called "Early Time HEMP" and is generated instantaneously at the moment of nuclear detonation. E1 is also called the "prompt gamma signal" because is created by the gamma rays released by the nuclear detonation that travel outward at the speed of light. Those gamma rays, traveling downward from the detonation, begin to strike air molecules at a height of 40 to 20 km (25 to 12 miles) and strip electrons from them. These high energy electrons are also directed downward towards the Earth. The Earth's gravity causes the electrons to spin; this

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[88] The fact that E2 will immediately follow E1 may allow E2 to cause damage, because the E1 has damaged or destroyed the devices designed to protect against E2.

[89] National Coordinating Center for Communications. (Feb 5, 2019). "Electromagnetic Pulse (EMP) Protection and Resilience Guidelines for Critical Infrastructure and Equipment", Version 2.2, National Cybersecurity and Communications Integration Center, Arlington, Virginia, p. 4. https://www.cisa.gov/sites/default/files/publications/19_0307_CISA_EMP-Protection-Resilience-Guidelines.pdf
https://www.cisa.gov/sites/default/files/publications/19_0307_CISA_EMP-Protection-Resilience-Guidelines.pdf

constitutes an electric current that creates a very large and powerful electromagnetic field, which will engulf entire geographic regions in a few billionths of a second[90] after the detonation.[91]

E1 primarily affects above-ground electrical conductors. While E1 can penetrate the Earth, most of E1 is reflected from Earth's surface (reflected E1 also can induce current and voltage). E1 does not affect lines buried 1-2 meters deep.[92] The electric fields generated by E1 are much more severe in intensity than the electric fields caused by natural events, such as lightning. Only special transient protectors are fast enough to protect integrated circuits against the high voltages and currents created by HEMP E1, which occurs so quickly that ordinary "surge protection" systems are unable to stop it.[93]

E1 Threat to the National Electric Grid

Although E1 poses no direct threat to the human body, E1 electromagnetic fields can induce damaging voltage and electrical currents into ***any*** electrically conductive object. Power transmission lines, which carry electricity long distances from electric power generating facilities, would be highly impacted.[94] The voltages and currents induced in these lines will disable or destroy the relays, sensors, and control panels found at all High Voltage Substations. This equipment controls the flows of electricity in and out of the Substation. A single HEMP (Figure 13) could severely damage equipment at more than 1700 Extra High Voltage (EHV)

[90] Interference Technology. (May 5, 2011). "High Power Electromagnetic (HPEM) Threats to the Smart Grid". https://interferencetechnology.com/high-power-electromagnetic-hpem-threats-to-the-smart-grid/
[91] Ibid, pp. 4-1 and 4-2. There is a relatively small "null" area that is not impacted, due to the complexities of how HE MP is formed, see Figure 9.
[92] The least coupling is for buried cables; often a meter or two below ground provides significant protection from E1 HEMP fields. The total driver of the coupling is the incident HEMP E1 pulse plus its reflection off the ground. Savage, Edward, James Gilbert, and William Radasky. (2010). "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid". Metatech Corporation, Meta R-320, p. 5-2. https://www.futurescience.com/emp/ferc_Meta-R-320.pdf
[93]Ibid, p. 2-35
[94] Op. cit. "Protecting Industry from HEMP and IEMI",

substations in the Eastern, Southeastern, and Central United States (Figure 14).[95] Simultaneously disabling these Substations would knock down the U.S. national electric grid in about half the continental U.S.

Figure 13: Exposure for E1 HEMP Burst at 170 km over Ohio[96]

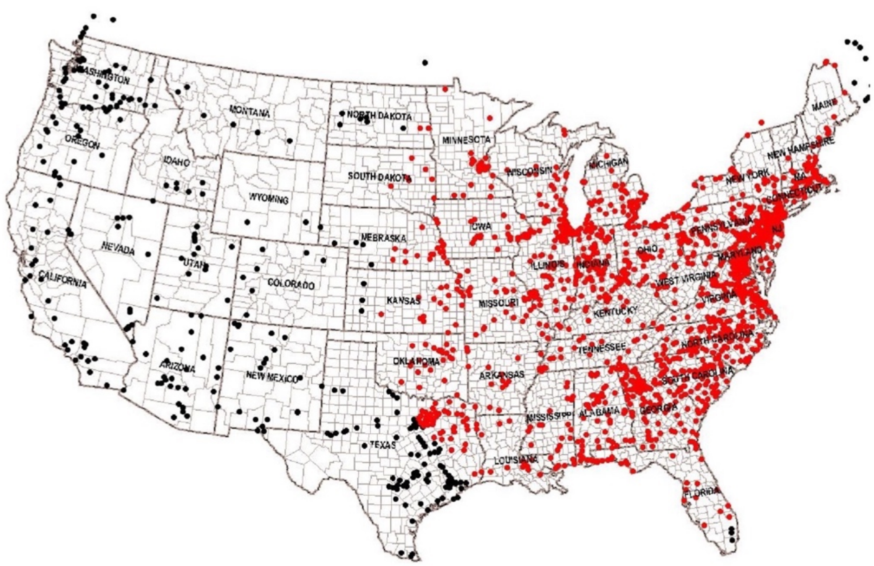

Figure 14: 1765 EHV substations at 345 kV and higher (83%) exposed by the burst in Figure 10[97]

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[95] Op. cit. "High-Frequency Protection Concepts for the Electric Power Grid", p. 2-5.
[96] Ibid.
[97] Ibid, p. 2-6.

E1 will also impact electric power distribution lines. Approximately 78% of all electric power is delivered to end users (residential, agricultural, industrial) through 15kV class distribution lines, which are likely to receive the maximum voltages and currents induced by E1.[98] Analysis of the E1 threat by the Metatech Corporation indicated that induced overvoltages, ranging from 200 kV to over 400 kV, would occur in these distribution lines over geographically widespread regions.[99] There are *tens of millions of insulators on these lines which would be damaged or destroyed by these extreme voltages*;[100] the loss of these insulators would likely cause a power grid collapse in the impacted regions.[101] (see Appendix 1)

E1 can damage and destroy integrated circuits found in all modern electronic devices

These high voltages and currents induced into power lines, telecommunication lines, and even small cables[102] can flow into unprotected circuits connected to the lines and wires, which allows HEMP E1 to enter all types of unshielded electronic devices (Figure 16). The E1 waveform differs from E3, in that it can directly penetrate through apertures in the external case of equipment, such as a computer, and induce significant currents and voltages at the circuit board level.[103]

Under ideal circumstances (using a non-Super EMP weapon), **HEMP E1 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 power lines**.[104] These high voltages and currents are

[98] Op. cit. "High-Frequency Protection Concepts for the Electric Power Grid", p. 2-9.
[99] Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", pp. 7-27.
[100] Personal correspondence with Dr. William Radasky, November 22, 2022.
[101] Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-11.
[102] Op. cit. "Protecting Industry from HEMP and IEMI", *In Compliance Magazine*
[103] Op. cit. High-Impact, Low-Frequency Event Risk to the North American Bulk Power System", p. 80.
[104] 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

many times larger than electrical transmission lines are designed to handle. The voltage and current signals that get generated on those lines will then multiply and move down the line, and flow into any circuits connected to the line (Figure 15).[105] E1 can also induce large voltages and currents in low voltage cables, in lengths as short as 10 meters.[106]

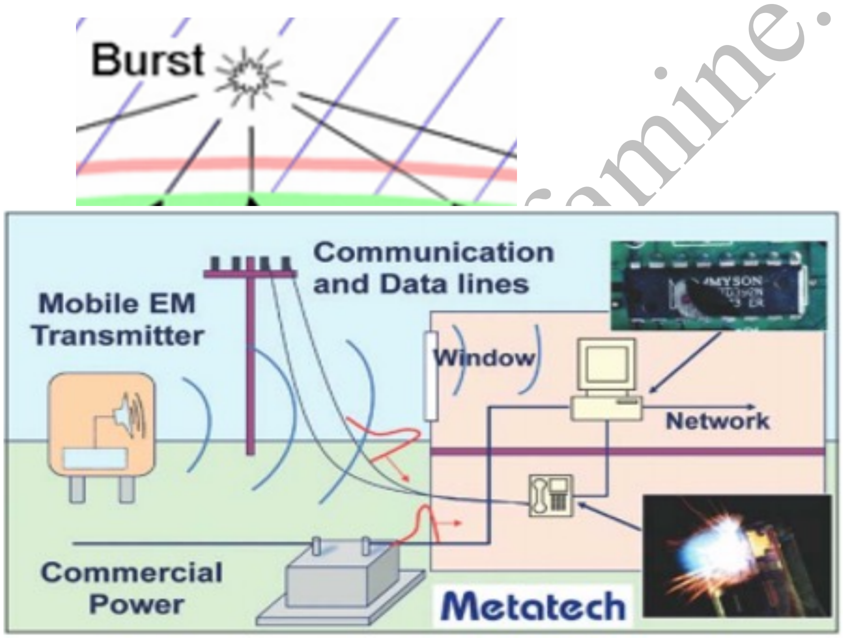

Figure 15: HEMP/EMP enters a structure via power and data lines and then enters all the electronic devices connected to this circuit.[107] This Figure illustrates EMP from a mobile Electromagnetic transmitter, as well as EMP from a High-altitude Electromagnetic Pulse.

Unprotected electronic devices that are powered on and connected to the incoming circuit are the most vulnerable, but even an unpowered system, which is attached to cables, can be

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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.

[105] Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 4-42.

[106] Op. cit. "Rebuttal to "The EMP threat: fact, fiction, and response"

[107] Adapted from Figure 1 from Radasky, W. (October 31, 2018). "Protecting Industry from HEMP and IEMI", In Compliance Magazine. https://incompliancemag.com/article/protecting-industry-from-hemp-and-iemi/ and Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", pp. 4-6.

vulnerable. With a peak E1 field of 50 kV/m (found within the center of Figures 21 and 22), even a short "antenna" 10 cm in length (4 inches) can experience a voltage of about 5000 volts.[108].

Modern microelectronics are over one million times more vulnerable to EMP than electronic systems of the 1960s and would easily be damaged or destroyed – on a regional basis -- by the EMP from a single low-yield nuclear weapon detonated high enough to cover, for example, the eastern United States.[109] Unshielded modern electronic devices with long, attached cables, are likely to be hard hit by the high voltages and currents generated by HEMP E1.[110] It seems likely that most unprotected modern electrical equipment and electrical systems (and especially those connected to the grid) would be damaged and left inoperable in large geographic regions affected by HEMP (Appendix 1).

The high voltages and currents induced by HEMP E1 can almost instantly damage, disable, and destroy the integrated circuits (also referred to as chips, or microchips) and solid-state electronics that are widely used in *all* modern electronic devices and control systems, which typically operate at *low voltage* (a few volts). Modern electronic devices typically contain these and are very susceptible to the high voltages and currents induced by HEMP E1 (Figures 17 and 18). Vulnerable integrated circuits and semiconductor electronics are ubiquitous; they are used in all computers, modems, routers, switches, programmable logic controllers, circuit boards, solid-state safety relays, and Supervisory Control and Data Acquisition (SCADA) devices.[111]

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[108] Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-35.
[109] Op. cit. "Rebuttal to "The EMP threat: fact, fiction, and response"
[110] Op. cit. Savage et al. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 6-4.
[111] Op. cit. "High-Frequency Protection Concepts for the Electric Power Grid", p. 7-7.

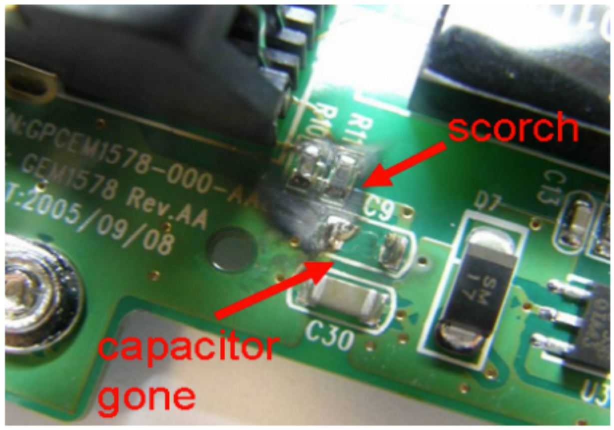

Figure 17: Capacitor damage due to large electrical pulse. The capacitor (C9) is gone, and there are scorch marks (C30 shows an undamaged capacitor)[112]

Figure 18: Integrated circuit (IC) damaged by large electrical pulse. The IC lid, normally flat, has bubbled, and is discolored from overheating.[113]

SCADAs are electronic control systems that are used for data acquisition and control over large and geographically distributed infrastructure systems. A SCADA unit (Figure 19) automatically and remotely monitors the operating state of a physical system by:

"*. . . providing an ongoing reporting of parameters that either characterize the system's performance, such as voltage or currents developed in an electric power plant, flow volume in a gas pipeline, and net electrical power delivered or received by a regional electrical system, or by monitoring environmental parameters such*

[112] Op. cit. Savage et al. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 6-2
[113] Ibid, Figure 6-3, p. 6-2.

as temperature in a nuclear power plant and sending an alarm when prescribed operating conditions are exceeded."[114]

Figure 19: Modern SCADA unit. This is the SEL-2032 (front view on top, back view on the bottom).[115]

SCADA systems are widely used in all parts of US critical infrastructure, such as in water supply, sanitation and waste systems, all transportation systems, all telecommunication networks, all financial transactions, oil and gas refining and distribution, and power generation facilities.[116] SCADA units are also indispensable components in the controls and operations of nuclear power plants, including emergency power and emergency cooling systems.[117] The 2008 Congressional EMP Commission concluded that:

"*SCADA systems are vulnerable to EMP insult. The large numbers and widespread reliance on such systems by all of the Nation's critical infrastructures represent a systemic threat to their continued operation following an EMP event."*[118]

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[114] Op. cit. "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack", p. 3.
[115] Op. cit. Savage et al. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 7-12.
[116] SCADA functions include real-time measuring, reading and adjustment of voltages, currents, reactance, line status (breakers, switches, re-closers, cap breaks, voltage regulations) and transformer status as well as identifying outages and even providing means to adjust load distributions and substation maintenance.
[117] Op. cit. "EMP and Space Weather and the Strategic Threat to America's Nuclear Power Stations: 2015 Final Report", pp. 24 and 34.
[118] Op. cit. "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack", Chapter 1, p. 9.

__Entire geographic regions subjected to enormous levels of HEMP E1__

Figure 20 illustrates the line-of-sight area covered by E1. The strongest E1 signals are produced by nuclear detonations that occur at altitudes between 40 km and 100 km (25 to 62 miles). It appears that the maximum E1 signals are produced at a height of about 75 km (42 miles).[119]

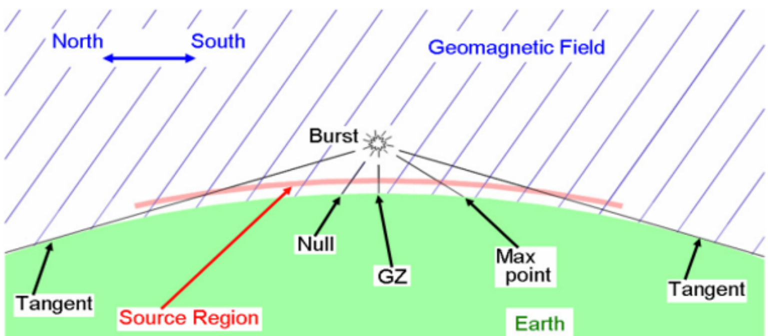

Figure 20: High-altitude nuclear detonation; E1 follows line of sight from burst point. (Source Region is point in atmosphere where E1 is formed, GZ is ground zero).[120]

The explosive power of the nuclear detonation can range from a few kilotons to tens of megatons, but the maximum E1 signal from all known (unclassified) types of nuclear weapons might vary by only about ten times in the energy fields they would create.[121]

Figure 21 illustrates the E1 coverage from a 500-kiloton detonation at varying altitudes. When detonated above the Earth's atmosphere, the X-rays, gamma rays, neutrons, and photon will travel great distances. These energy beams will damage and destroy orbiting satellites.[122]

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119 Op. cit. "EMP and Space Weather and the Strategic Threat to America's Nuclear Power Stations: 2015 Final Report", p. 2-13
120 Ibid, p. 2-16
121 Ibid, p. 4-6.
122 Critical National Infrastructures. (April 2008). "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack", p. 160. http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf

Note that the effects of HEMP E3 are maximized when a nuclear detonation occurs between 130 and 500 km altitude (higher than the burst heights that optimize HEMP E1).[123] [124]

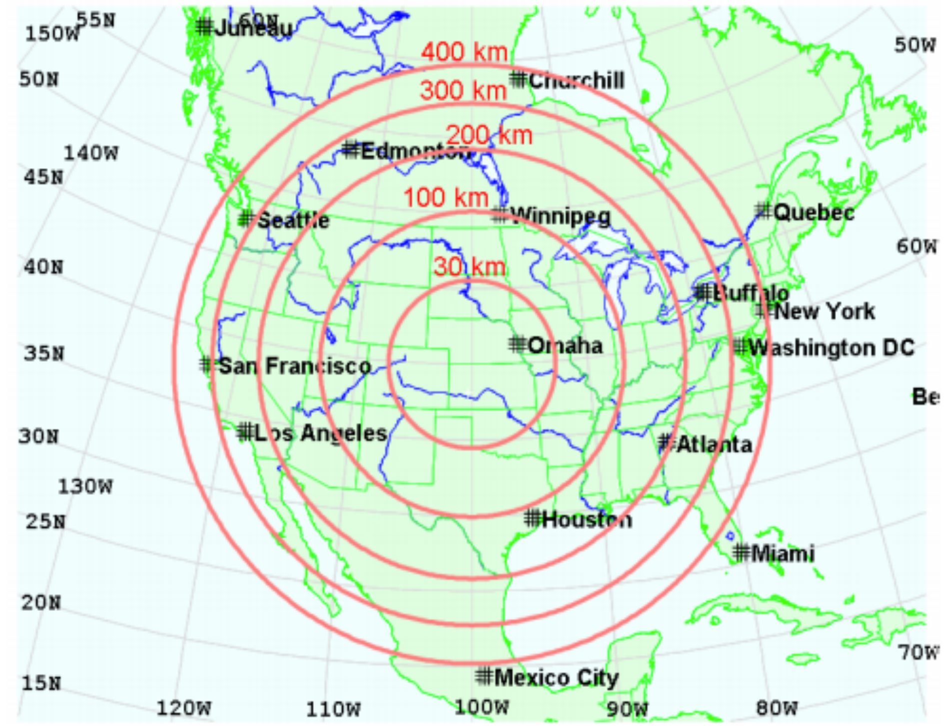

Figure 21: The red circles show the regions exposed to E1 Hemp from varying heights of burst (nuclear detonation). At 400 km height, all of the US is exposed.[125]

The optimization for E1 and E3B regarding Height of Burst is slightly different, but it is possible to get close to an altitude for detonation what will maximize both. E3B could be a more likely choice for war planners, as they can combine the effects of E1 and E3B with a single HEMP. For E3 total yield is most important, but for E1 the gamma ray output is the most

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[123] Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 1-2

[124] In my opinion, the data indicates that it is possible for war planners to combine both the E1 and E3 effects in a single detonation (especially if a super-EMP weapon were used) at an altitude of about 100km to 130 km, which would have the capability to bring down the national electric grid, as well as maximizing damage to the integrated circuits required to operate much of the national critical infrastructure. Several strategically placed detonations could certainly accomplish this goal.

[125] Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-15. While higher altitudes will decrease the intensity of the E1 incident energy fields, this may be compensated with the use of a Super-EMP weapon. The higher altitude will increase the coverage of HEMP E3, which will damage or destroy Large Power Transformers and high-speed relays and circuit breakers.

important; as previously mentioned, the gamma ray output does increase as the total yield increases, although not proportionately.[126]

E1 incident fields induce high voltage and currents into electrically conductive materials

The process in which HEMP E1 acts to induce current into electrically conductive materials is a complex phenomenon, which is described as "electromagnetic coupling".[127] This complexity makes it virtually impossible to precisely predict the voltages that E1 will induce in a variety of circumstances.[128] [129] Consequently, many good scientists tend to shy away from making more than general predictions about the extent of damage E1 can inflict (good scientists consider exaggeration to be a sin).[130] Yet it is not unrealistic to assume that many unshielded modern electronic devices (especially those connected to the grid) are likely to be disrupted, damaged, or destroyed if they are located within the regions exposed to E1 incident fields of 10 kV/m (or greater), because the maximum voltages and currents induced by these fields will far exceed the rated capacity of solid-state electronics that typically at a few volts.[131]

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126 Personal correspondence with Dr. William Radasky. Nov 22, 2022.

127 Electromagnetic signals, such as E1 HEMP, generate voltages and currents on conductors exposed to the fields. E1 HEMP coupling is like any other electromagnetic coupling. The EM fields encounter a conductor and induce voltage and current signals on that conductor. Vulnerability issues occur when the conductor connects to a circuit with parts that could be destroyed or upset. P. 2-37

128 Yet the maximum peak E1 HEMP from all known nuclear weapons might vary by only about an order of magnitude, and sometimes the peak E1 HEMP from a low yield weapon can be higher than peak E1 HEMP from another weapon with a much higher yield. Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 4-6.

129 The E1 HEMP field varies as a function of position, its arrival angle relative to the Earth's surface, as well as the polarization of the field relative to the cables or electrically conductive materials where coupling occurs. In other words, E1 magnetic fields are directional, and it is only the component of E parallel to the line that couples to the line. Op. cit. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", pp. 5-1 and 4-42. Also, personal correspondence with Dr. William Radasky, Nov 22, 2022.

130 Yet E1 HEMP coupling is not unlike any other electromagnetic coupling where electromagnetic fields encounter a conductor and induce voltage and current signals on that conductor. If the conductor connects to an unprotected circuit with parts that could be destroyed or upset, then damage results. P. 2-37

131 As the devices in our modern systems become smaller, their operating voltages get lower, and their operating frequencies get higher, E1 HEMP looks to be more of a threat. The coupled signal can easily be hundreds or thousands of volts, while electronics operate at a few volts. The E1 pulse can last for many time cycles, and also have significant energy at system operating frequencies (100's of megahertz or higher). The high density of transistors and other devices on an integrated circuit means each is very small – so that even a small amount of

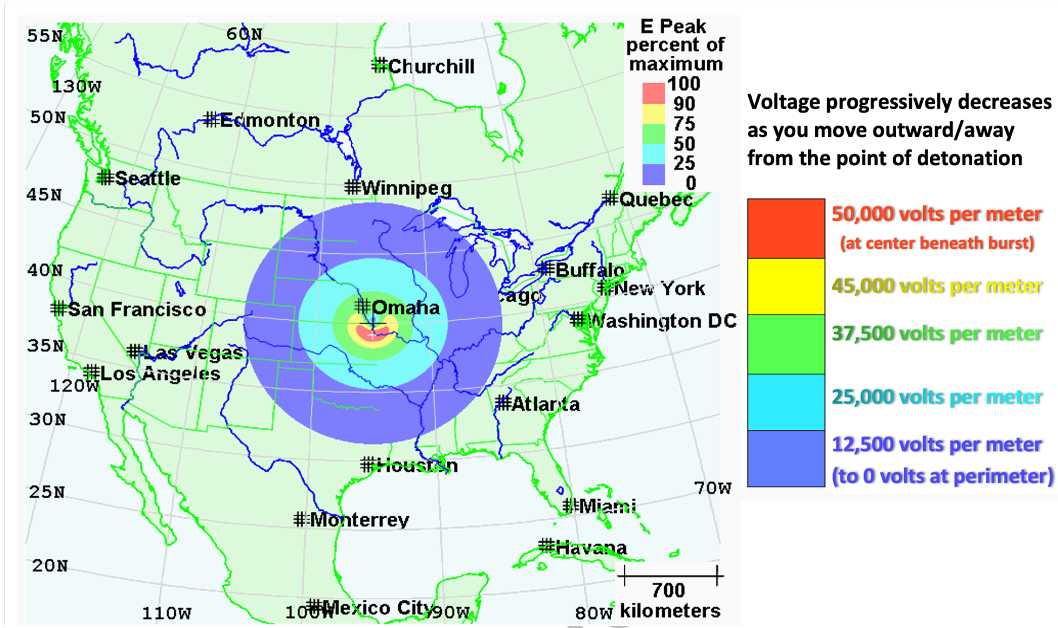

Figure 22: HEMP E1 created by 500-kiloton nuclear detonation[132] at a height of 75 km (42 miles) over Omaha, Nebraska.[133]

Figure 22 is derived from a Figure created by the Metatech Corporation[134], which illustrates the maximum possible voltages that could be induced into electrically conductive surfaces from a 500-kiloton nuclear detonation (non-super EMP weapon) at an altitude of 42 miles. Figure 21 can be used for a general approximation for the maximum E1 incident fields created by HEMP, but the maximum induced voltage and current values will not be uniform, as these maximum values will vary with position on the ground based on the weapon yield, the weapon design, and the burst height and the location of the burst relative to the local geomagnetic field.[135]

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energy can be very significant; the smaller the mass that absorbs a given amount of energy, the higher the mass's temperature increase from the absorbed energy. P. 6-3, 6-4 E320

[132] Op. cit. Savage et al. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-25.

[133] Op. cit. Savage et al. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-30.

[134] Op. cit. Savage et al. "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid", p. 2-30.

[135] Voltage is induced to conductors via coupling of the E1 electromagnetic field to conductors, which is controlled by the amount of electric field parallel to the conductor, but also to the angle that it sweeps along the conductor and also the length of the conductor and its loads. Coupling to short cables (i.e. 1 meter) is very simple - 50 kV/m will

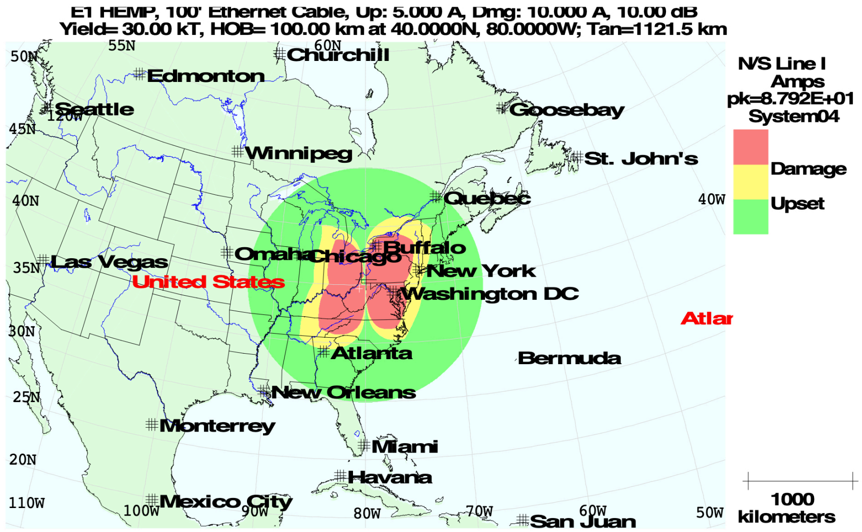

Figure 22: 30-kiloton detonation at 62 miles height induces damaging currents into 100-foot unshielded ethernet cable. Any unprotected integrated circuits within electronic devices connected to these lines will likely be damaged or destroyed.[136]

The Cybersecurity Division of the Cybersecurity and Infrastructure Security Agency (an agency of the U.S. Department of Homeland Security) issued a 2019 report entitled "Electromagnetic Pulse (EMP) Protection and Resilience Guidelines for Critical Infrastructure and Equipment".[137] This unclassified report contained the Figures reproduced below in Figures 23 through 24, which depict the peak pulse of the E1 incident energy fields created by the detonation of a 30-kiloton, 100-kiloton, and 1-megaton nuclear warhead over the United States.[138] The red zones indicate the geographic regions where electronic devices connected to 100-foot unshielded ethernet cables will likely be damaged or destroyed by high voltages and currents induced by HEMP E1.

produce a voltage of 50 kV across that meter if the field is parallel. Personal correspondence with Dr. William Radasky, March 12, 2021.

[136] Op. cit. "Electromagnetic Pulse (EMP) Protection and Resilience Guidelines for Critical Infrastructure and Equipment" from Figure 10, p. 14.

[137] Cybersecurity Division of the Cybersecurity and Infrastructure Security Agency, National Coordinating Center for Communications, February 5, 2019. "Electromagnetic Pulse (EMP) Protection and Resilience Guidelines for Critical Infrastructure and Equipment", version 2.2 UNCLASSIFIED.
https://www.cisa.gov/sites/default/files/publications/19_0307_CISA_EMP-Protection-Resilience-Guidelines.pdf

[138] These Figures were created from an unclassified code called EMAT that the Metatech Corporation created for Homeland Security.

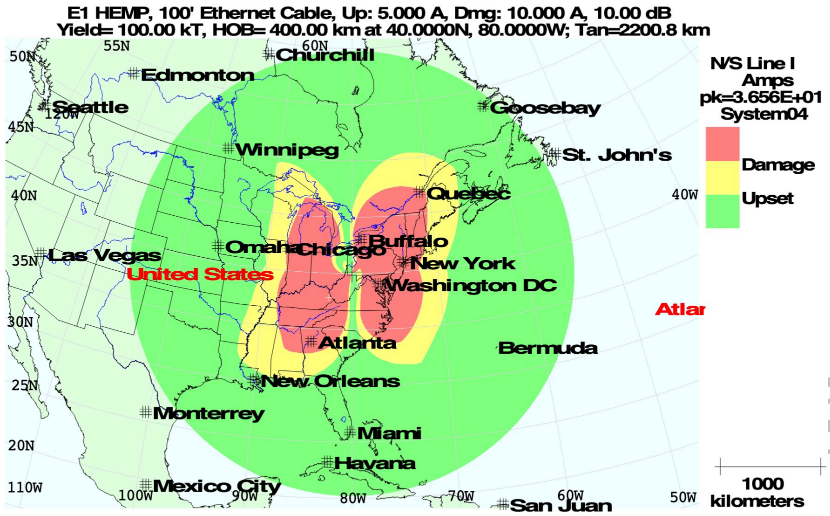

Figure 23: 100-kiloton detonation at 248-mile height induces damaging current into 100-foot unshielded ethernet cable. Unshielded modern electronic devices connected to these lines will likely be damaged or destroyed[139]

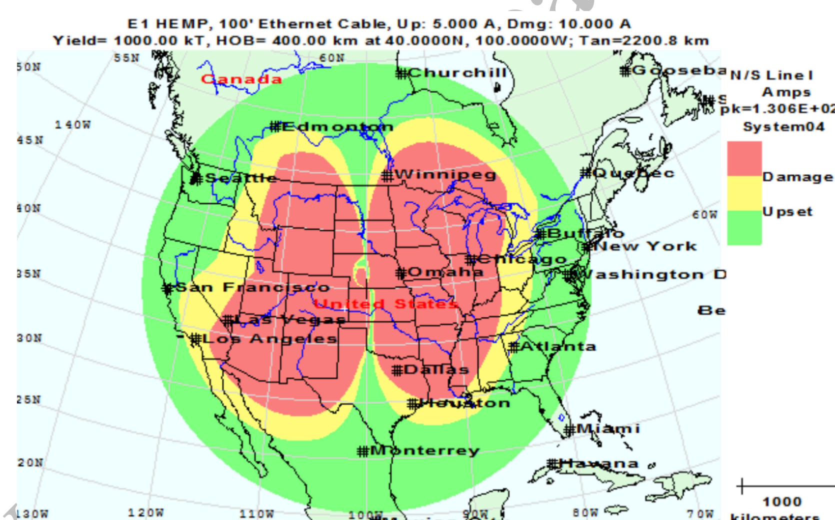

Figure 24: 1-megaton detonation at 248-mile height induces damaging current into 100-foot unshielded ethernet cable. Unshielded modern electronic devices connected to these lines will likely be damaged or destroyed[140]

The US Department of Defense apparently accepts that HEMP E1 poses a major threat to modern electronics, as it reportedly uses classified software that predicts the HEMP E1 produced by a 100-kiloton weapon will *destroy* all unprotected integrated circuits and SCADA control

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139 Ibid, from Figure 9, p. 13.
140 Ibid, from Figure 24, p. 44.

units within a 9200 square mile area.[141] This figure corresponds with the unclassified and authoritative studies by the Metatech Corporation, which predict peak incident energy fields of HEMP E1 will range up to 50,000 volts per meter (Figure 22) in an area of approximately 9000 square miles; 37,500 to 50,000 volts per meter in an area of 30,000 square miles, and 12,500 to 50,000 volts per meter in an area of 70,000 square miles (with the lowest voltages at the perimeter progressively increasing towards the highest voltages in the center regions).[142]

Super-EMP Weapons Generate Super Levels of E1

Super-EMP weapons are designed to only generate HEMP E1.[143] According to Russian open sources, a Super-EMP weapon can generate a peak E1 [incidence] field of 200,000 volts per meter (kV/m).[144] Russian open-source military writings claim that Super-EMP weapons generate such powerful fields that even hardened U.S. strategic forces would be vulnerable.[145]

The Chinese military also describe a super-EMP weapon, stating that the E1 field "produced by nuclear EMP is about 10 to 100 kV/m and can penetrate and melt any electronic components."[146] Note that this paper uses 50 kV/m as the maximum incidence field created by HEMP E1 (see Figure 14). In other words, this paper describes the effects of nuclear weapons that produce a maximum E1 incident energy about one-quarter to one-half of the incident energy fields produced by the Super-EMP weapon described in Russian and Chinese military sources. Thus, the effects of HEMP predicted in this paper could be significantly more severe, especially

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141 I base this statement upon my own personal correspondence with authoritative source within the US government.
142 An "incident energy field" is defined as the "Field strength of a sky wave without including the effects of earth reflections at the receiving location".
143 Op. cit. "Rebuttal to "The EMP threat: fact, fiction, and response", p. 2.
144Vaschenko, A. (November 1, 2006). "Russia: Nuclear Response to America Is Possible Using Super-EMP Factor", "A Nuclear Response To America Is Possible," Zavtra,
145 Vaschenko, A., Belous, V. (April 13, 2007); "Preparing for the Second Coming of 'Star Wars", *Nezavisimoye Voyennoye Obozreniye* translated in *Russian Considers Missile Defense Response Options* CEP20070413330003.
146 Zhao Meng, Da Xinyu, and Zhang Yapu, (May 1, 2014). "Overview of Electromagnetic Pulse Weapons and Protection Techniques Against Them" Winged Missiles (PRC Air Force Engineering University.

if Super-EMP weapons are employed. Extreme cold and hot weather conditions would also increase the damage caused by HEMP.

Part 2: Effects of HEMP E1 on Nuclear Power Plants and Spent Fuel Pools

Executive Summary

The U.S. Nuclear Regulatory Commission (NRC) considers U.S nuclear power plants to be in no danger from EMP. The NRC views EMP as a "beyond-design-basis event", which does not have to be protected against with the use of "safety-grade" systems, structures, and components."[147] 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.[148]

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).

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[147] 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

[148] Ibid, p. 59.

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 (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 (see Part 1), 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[149]). 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

149 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

generators[150], and to the ancillary plant[151]. And even with 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.

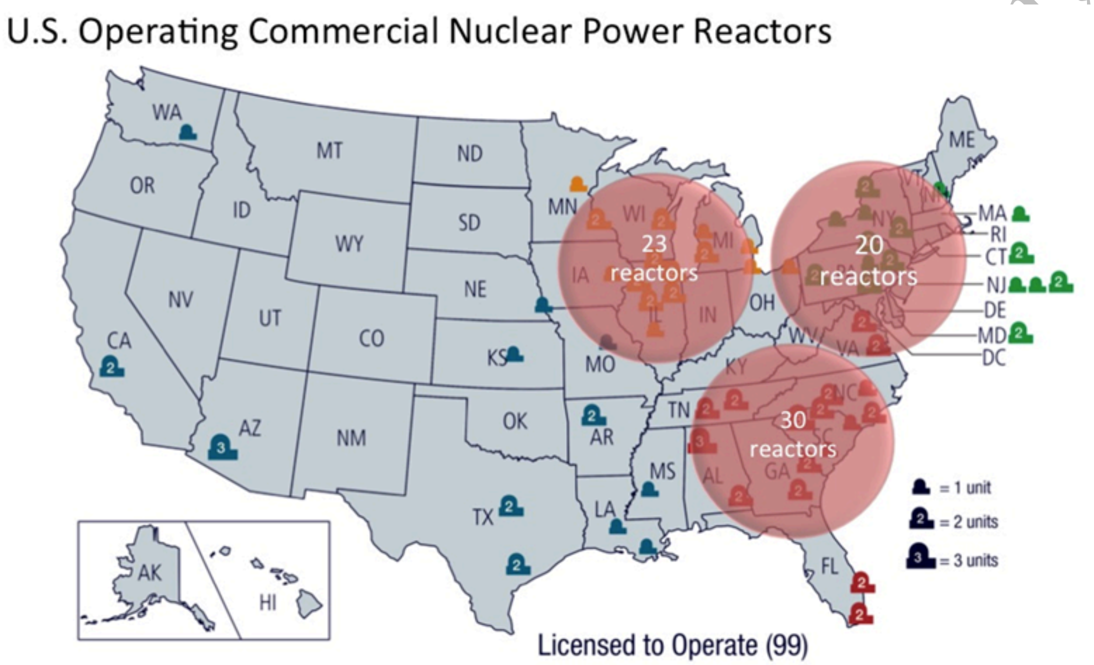

Figure 25: The number of operating nuclear reactors (20 to 30 in each zone) that would be within the areas predicted to have HEMP E1 levels of 12,500 volts per meter or greater**;** each zone created by one 500-kiloton warhead detonated at an altitude of 75 km (42 miles).[152]

A failure of the ECCS to remove heat from the reactor core can rapidly cause the temperature in an uncooled reactor core to 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

[150] 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/
[151] 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.
[152] 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.

the reactor core.[153] 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 25).

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 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.[154] The pools each typically contain about 4 to 5 times more long-lived radioactive fission products than are found inside each reactor core.[155] These pools contain some of the highest concentrations of radioactivity on the planet, yet

[153] "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

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

[155] "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/

they are located *outside* of the primary containment vessel that houses the nuclear reactor,[156] 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.[157] 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.[158] The water in the pool will then "boil-off", exposing the spent fuel rods to steam and water.[159]

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.[160] The radioactive fallout released by a single spent pool fire could easily leave *tens of thousands of square miles uninhabitable for centuries.*[161] [162] Dozens of spent fuel pool fires – created by a single HEMP – could leave much of the U.S. uninhabitable for centuries.

What is the Solution to the Danger HEMP Poses to U.S. Nuclear Power Plants?

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[156] 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/
[157] 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/
[158] 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
[159] 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.
[160] 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
[161] Op. cit. "Electromagnetic Defense Task Force (EDTF) Report 2.0, LeMay Paper No. 4", page 13.
[162] Op. cit. "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States"

Technology exists that could significantly reduce danger posed by HEMP to the safety systems in U.S. nuclear power plants. Adding shielding to protect the Emergency Core Cooling Systems, backup electrical power systems, and the control rooms at these plants could considerably reduce the risk of meltdown of the reactors and boil-offs of the spent fuel pools. The estimated costs to add this protection are in the billions of dollars, which is a small fraction of what the U.S. spends each year on its defense budget.

The danger posed by the destruction of spent fuel pools could also be reduced by (1) removing most of the spent fuel from the pools (that fraction which has cooled enough to be safely handled) and (2) placing it in thick-metal dry cask storage, and then storing the casks in hardened buildings where it can be continuously monitored. However, spent fuel must be isolated from the biosphere for at least 100,000 years, which is a rather long time to expect people to be able to monitor. 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). American citizens, along with many other people in the world, remain very much at risk from the catastrophic effects of HEMP (and GMD).[163]

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

HEMP E1 Threat to Nuclear Power Plants and Nuclear Reactors

> *EMP [Electromagnetic Pulse] and GMD (Geomagnetic Disturbance] are part of a unique risk set which has the capability of causing systematic wide-spread failures which can lead to the simultaneous and catastrophic meltdowns at nuclear power stations and research reactors across the U.S.*" – "Electromagnetic Pulse and Space Weather and the Strategic Threat to America's Nuclear Power Stations", American Leadership and Policy Foundation, Final Report, 2015

If HEMP brings down the U.S. national electric grid, a loss of off-site power will immediately trigger emergency shutdowns of the nuclear reactors at U.S. nuclear power plants. Any plant operating at full power will have a massive amount of residual decay heat (from radioactive fission products in the uranium fuel) remaining in the reactor core post-shutdown. This heat *must* be continuously removed from the core for a period of days, until the remaining heat is decreased to a low enough level that it can no longer damage the core. Lack of cooling (forced flow of water through the reactor core) after an emergency shutdown will result in the destruction of the core and release of radioactive material into the environment.[164] If the high voltages and currents created by HEMP E1 disable the emergency power and emergency cooling systems that are required by nuclear power plants to safely cooldown their reactor cores, then it is likely that nuclear plants that are unprotected from HEMP will self-destruct.

U.S. Nuclear Power Plants Are Not Designed to Withstand EMP

In 2022 there were 53 nuclear power plants with 92 nuclear reactors operating in 28 U.S. states,[165] including 62 Pressurized Water Reactors (PWR) and 30 Boiling Water Reactors

[164] Hoffmeister, G. (2017). "Emergency power solutions for nuclear power plants – case studies, considerations, and conclusions", The Institute of Engineering and Technology, Reference Article, doi: 10.1049/etr.2016.0161 ISSN 2056-4007. http://s7d2.scene7.com/is/content/Caterpillar/CM20170217-55802-65351
[165] Nuclear Energy Institute. (Jan 1, 2023). "U.S. Nuclear Plants". https://www.nei.org/resources/us-nuclear-plants

(BWR).[166] and they all are *essentially unprotected and significantly at risk from the widespread effects of an Electromagnetic Pulse (EMP).* None of these plants were designed or constructed to survive a massive EMP event. And no steps have yet been taken to shield these facilities from EMP because the US Nuclear Regulatory Commission (NRC) regards EMP as a "beyond-design-basis event," which does not have to be protected against with the use of "safety-grade" systems, structures, components, or safety training.[167] EMP is also not on the list of FEMA's National Planning Scenarios, so no emergency training plan for EMP exists for nuclear power plants.[168] [169]

The NRC bases its assertion on an outdated 1982 study that says, "The likelihood that individual components examined will fail is small; therefore, it is unlikely that an EMP event would fail sufficient equipment so as to prevent a safe [cold] shutdown."[170] The NRC contends that this was confirmed in 2009 by another study done by the Sandia National Laboratory, "Assessing Vulnerabilities of Present Day Digital Systems to Electromagnetic [EM] Threats at Nuclear Power Plants".[171]

This assertion has been contested by many experts outside the nuclear industry, as well as in the U.S. military. In 2019, a U.S. Air Academy report noted that no comprehensive testing had been done at operating or recently closed nuclear power plants to verify the NRC's belief that

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166 U.S. Energy Information Administration. (July 13, 2022). "Nuclear Explained: Nuclear Power Plants". https://www.eia.gov/energyexplained/nuclear/nuclear-power-plants-types-of-reactors.php
167 Op. cit. "Electromagnetic Defense Task Force (EDTF) Report 2.0, LeMay Paper No. 4", Appendix 1, pp. 53.
168 Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. (April 2008). "Critical National Infrastructures", p.60. http://www.empcommission.org/docs/A2473-EMP_Commission-7MB.pdf
169 United States Dept of Homeland Sec. (2007), National Preparedness Guidelines. http://www.fema.gov/pdf/emergency/nrf/National_Preparedness_Guidelines.pdf
170 Ericson, D. et al. (1983). "2 Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems", Sandia National Laboratories. http://prod.sandia.gov/techlib/access- control.cgi/1982/822738-2.pdf
171 Op. cit. "Electromagnetic Defense Task Force (EDTF) Report 2.0, LeMay Paper No. 4", p. 55 and p. 67.

EMP posed no threat to nuclear power plants.[172] A report by the Electromagnetic Defense Task Force (EDTF), created by members of the U.S. Air Force Air University, stated:

> *"Over the last few decades, the U.S. grid and technologies that use it to function have become codependent. As a result, present design basis requirements (risk mitigation features required for individual power stations to receive operations certification) from NRC do not address EMP or GMD as a risk to nuclear power stations because stations are assumed to have constant access to a reliable power grid."*[173]

The EDTF listed a number of concerns to the NRC regarding the current status of U.S. nuclear power plants:

- Lack of credible research on EMP impacts to nuclear power stations.
- Lack of comprehensive physical facility testing.
- EMP will cause a prolonged station blackout (loss of off-site power and on-site EDG [Emergency Diesel Generator] and/or electrical distribution systems).
- EMP may impact control rooms and sensitive electronics.
- Post-shutdown EDGs may not function
- Post-EMP logistics to the nuclear power station, including diesel, would be exhausted after one week (seven days).
- Post EMP, spent fuel pools may not have adequate electrical power to the cooling pumps
- Before an EMP or station blackout, it might make sense to have more spent fuel in dry cask storage in order to reduce the risk of a self-sustaining zirconium fire in the spent fuel pool in the event of an extended loss of cooling[174]

The NRC did respond to these concerns but made no fundamental change in their position.

Thus, no US nuclear power plant (currently under license) has been designed, constructed, or retrofitted to survive EMP (or an attack with a non-nuclear Intentional Electromagnetic Interference device[175]), GMD, or a substantial interruption of the power grid

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172 Ibid. pp. 55-73.
173 America Leadership and Policy Foundation. (June 2015). "Electromagnetic Pulse and Space Weather and the Strategic Threat to America's Nuclear Power Stations: Final Report", p. 14. https://www.emptaskforce.us/wp-content/pdf/Electromagentic-Pulse-and-Space-Weather-Final-Report-2015.pdf
174 Op. cit. "Electromagnetic Defense Task Force (EDTF) Report 2.0, LeMay Paper No. 4", pp. 55-58.
175 Op. cit. "High-Frequency Protection Concepts for the Electric Power Grid"

(longer than 7 days).[176] No training of personal and no emergency procedures are set up to deal with EMP or HEMP. Many of the circuit boards, control units and electronics likely to be damaged by the high voltages and currents induced by E1 are not likely to be stored on-site.

In 2012, following the meltdown of three nuclear reactors at Fukushima Daiichi, the NRC issued NEI 12-06, Order EA-12-049, entitled "A Diverse and Flexible Coping Strategy (FLEX)"; the NRC issued guidance which required U.S. nuclear power plants to develop strategies " . . . capable of mitigating a simultaneous loss of all AC power and loss of normal access to the normal heat sink and have adequate capacity to address challenges to core cooling, containment, and SFP cooling capabilities at all units on a site subject to this Order."[177] Nuclear power plants were subsequently required to keep on-site FLEX equipment that includes portable generators, pumps, and equipment to supply reactor cooling in the event the installed plant equipment is damaged.[178] There is no indication that any of the FLEX equipment has been shielded against HEMP E1.

Vulnerable Components of Emergency Electrical Power Systems (see Appendix 1)

The Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack stated:

> "Electronics have largely replaced all the electromechanical devices in older plants and are used exclusively in plants of the past one or two decades. Even generator exciters now have microprocessors and analog-to-digital converters. These electronics and, thus, the power plant itself

[176] Op. cit. "Electromagnetic Pulse and Space Weather and the Strategic Threat to America's Nuclear Power Stations: Final Report, p. 15.
[177] Nuclear Regulatory Commission. (May 2012). "Diverse and Flexible Strategies (FLEX) Implementation Guide", p. 10. https://www.nrc.gov/docs/ML1214/ML12143A232.pdf
[178] U.S Department of Energy, Office of Nuclear Energy. (August 2020). "Integration of FLEX Equipment and Operator Actions in Plant Force-=On-Force Models With Dynamic Risk Assessment, Light Water Reactor Sustainability Program", p. 1. https://lwrs.inl.gov/Physical%20Security/Integration_FLEX_Equipment_Operator_Actions.pdf

> are highly vulnerable to EMP assault. Identifying and locating damaged generation plant equipment with electronic sensors and communication interdicted and/or unreliable due to EMP and repairing the system would be a complex and time-consuming process, even when personnel and parts are readily available."[179]

Should HEMP disable or destroy critical components of the emergency power and emergency cooling systems that are required to safely shut down the reactor, the plant operators will have to rely on ad-hoc procedures, on-the-spot innovation, and whatever equipment that would remain functional to prevent the nuclear reactors and spent fuel pools from self-destructing.

Emergency Diesel Generators (see Appendix 2)

Electrical power is required for a nuclear power plant to use its Emergency Core Cooling System (ECCS) and its Essential Service Water System (ESWS).[180] If the national electric grid goes down and off-site electrical power is lost, the Emergency Diesel Generators (EDGs) are the primary source of backup electric power for a nuclear power plant (with the sole exception of hydroelectric generating units for the Oconee nuclear plant in South Carolina). The EDG system usually has redundancies including multiple sets and twinned sets, sometimes separated by distance.[181]

The Nuclear Regulatory Commission requires that EDGs function within 10 seconds following an emergency shutdown triggered by loss of offsite power.[182] The EDGs receive their

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[179] Op. cit. "Critical National Infrastructures", p.35.
[180] International Atomic Energy Agency. (2019). "Passive Safety Systems in Water Cooled Reactors: An Overview and Demonstration with Basic Principle Simulators", Training Course Series 69, Vienna, p. 13. https://www-pub.iaea.org/MTCD/Publications/PDF/TCS-69web.pdf
[181] Clarke, M. (June 2020). "Battery Backup", Nuclear Engineering International Magazine. https://secure.viewer.zmags.com/publication/4d4161a2#/4d4161a2/30
[182] Nuclear Regulatory Commission. (September 29, 2011).,"Chapter 1: Diesel Generators as Emergency Power Sources". https://www.nrc.gov/docs/ML1122/ML11229A065.pdf

initiation signals (loss of voltage signals) from the initiation logic circuits, which, if unshielded, are vulnerable to HEMP E1.[183] The EDGs – if still functional – may not automatically start because the SCADA unit(s) within the control room of the nuclear power plant could be disabled, damaged, or destroyed by the effects of HEMP E1.

The EDGs have at least four solid-state components and circuit boards that must function for them to operate: the Diesel Generator Load Sequencer, the Diesel Generator process control sensors, the Battery Charger, and the AC Static Inverter.[184] Within the EDGs are the speed monitoring and stop circuitry, the excitation systems (the system that provides field current to the rotor windings on the generator), the Fault Shutdown and Monitoring Circuits, and the Starting Circuit. There are also sensors in the cooling system of an EDG.[185] These components all utilize solid-state electronics, and if left unprotected, are vulnerable to damage or destruction by HEMP E1; the EDGs will not run if their internal circuits are disabled, damaged, or destroyed (see Appendix 1). These considerations will also hold true for on-site FLEX EDGs, although they may be less susceptible to the effects of HEMP E1 if they are not plugged into any electrical supply system.

EDGs are stored in a separate building or room, outside the control room and containment vessel,[186] whose doors may automatically lock with failure of power systems. This would make them difficult to access without breaking into the room, which would add another obstacle to making the EDGs operational. Any staff attempting to get the EDGs in service would

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183 Peach Bottom Atomic Power Station, Unit 2, Technical Specifications. (N.D.). "Emergency Core Cooling System (ECCS) Instrumentation, B.3.3.5.1.", p. 3.3-98. https://www.nrc.gov/docs/ML0211/ML021190024.pdf
184 America Leadership and Policy Foundation. (June 2015). "Electromagnetic Pulse and Space Weather and the Strategic Threat to America's Nuclear Power Stations: Final Report", p. 28. https://www.emptaskforce.us/wp-content/pdf/Electromagentic-Pulse-and-Space-Weather-Final-Report-2015.pdf
185 Union of Concerned Scientists, "Nuclear Power(less) Plants", October 2015, https://allthingsnuclear.org/dlochbaum/nuclear-powerless-plants
186 Nuclear Tourist. (Dec 8, 2005). "Key Areas and Buildings at the Nuclear Power Plant Site". http://www.nucleartourist.com/areas/areas.htm

also be unable to communicate with anyone back in the control room because the communication systems and cell phones would be inoperable without electricity after a massive HEMP.

EDGs used at nuclear power plants are very large generators that require hundreds of gallons of fuel for each hour of operation.[187] [188] A typical EDG can require 400 gallons of diesel per hour to operate, which would equal 4800 gallons per day. The NRC requires U.S. nuclear power plants to keep a 7-day supply of diesel fuel on-site to power the EDGs in case it is needed for emergency use;[189] that would equate to more than 33,000 gallons per EDG (normally two EDGS are present for each reactor at U.S. nuclear power plants). If HEMP takes out most of the U.S. national electric power grid, it could prove impossible to continue to supply nuclear power plants with huge quantities of diesel fuel if the EDGs were required to run for prolonged periods of time.

Battery Banks (see Appendix 2)

Figure 26: Battery Bank at U.S. Nuclear Power Plant[190]

[187] Earthsafe Systems, Inc. (2023). "YQA Generator Day Tanks, 07.12 How much fuel does a generator consume". https://www.earthsafe.com/resources/yqa07-generator-day-tanks-faq

[188] A 6000 kW generator operating at full load uses approximately 427 gallons of diesel fuel per hour, see Global Power Supply. (2023). "Power Generation Calculators". https://www.globalpwr.com/power-calculator/

[189] Nuclear Regulatory Commission. (March 2007). Standard Review Plan, NUREG-0800, 9.5.4. Emergency Diesel Fuel Oil Storage and Transfer System. https://www.nrc.gov/docs/ML0706/ML070680388.pdf

[190] Lochbaum, D. (October 20, 2015). "Nuclear Power(less) Plants", Union of Concerned Scientists. https://blog.ucsusa.org/dlochbaum/nuclear-powerless-plants/

A large battery bank is a secondary source of emergency electrical power for nuclear power plants (Figure 26). If the EDGs fail to operate, the only remaining source of electricity is direct current (DC) from onsite battery banks.[191] The batteries are normally kept charged with alternating current (AC) through inverters and chargers using offsite power (loss of offsite power means they will be unable to be recharged, and unprotected inverters will also be damaged or destroyed by HEMP E1). The batteries are designed to supply power to emergency equipment needed to cool the reactor core for a period of 4 to 8 hours; the NRC and plant designers have always assumed that either offsite power is restored or at least one of the EDGs will be restored to operation within this time frame.[192]

Batteries produce DC power that must be converted to AC power required by the electrical system at a nuclear power plant. Nuclear Engineering International states that "Modern technology for converting between DC and AC uses large-scale solid-state electronics that is very reliable."[193] [194] HEMP E1 will damage or destroy the unprotected solid-state electronics and integrated circuits found in the rectifiers, inverters, and the switching and monitoring systems, which are required by the battery bank to convert the DC current supplied by the battery bank to useable AC current. Without a functioning DC-AC interface, the Battery Bank will be unable to supply emergency power to the operate the many electrical components within the emergency systems required for a nuclear power plant to safely shutdown.

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191 Programmable logic controllers, which are highly susceptible to damage from HEMP E1, are also used to assign load sequences to backup electric power supplies at nuclear power plants. Gonzalez, R., Bible, C. (April 1994). "Application of PLCs for nuclear plant emergency load sequencers", Proceedings of SOUTHEAST CON '94", DOI: 10.1109/SECON.1994.324301 https://ieeexplore.ieee.org/document/324301

192 Union of Concerned Scientists, "Nuclear Power(less) Plants", October 2015, https://allthingsnuclear.org/dlochbaum/nuclear-powerless-plants

193 Nuclear Engineering International. (July 20, 2020). "Battery Backup for Nuclear Power Plants". https://www.neimagazine.com/features/featurebattery-backup-for-nuclear-power-plants-8037728/

194 Nuclear Engineering International. (July 20, 2020). "Battery Backup for Nuclear Power Plants". https://www.neimagazine.com/features/featurebattery-backup-for-nuclear-power-plants-8037728/

Emergency electric power is also required for plant communications. Without an operational plant communication system, plant operators will not be able to communicate with anyone outside the control room (landlines and cell phones will also not be operating after HEMP). The loss of instrument function will mean that plant operators will be unable to monitor water levels, temperature, and pressure within the Reactor Pressure Vessel. Operators and plant personal will also be working in the dark, as emergency power is required for lighting. If they attempt to repair any of the damaged electronics (and have the replacement parts available), they will have to make the repairs without schematics, as those are all stored online.

Vulnerable Components of Active Emergency Core Cooling Systems (ECCS)

Emergency Core Cooling Systems (ECCS) are designed to safely shut down a nuclear reactor during accident conditions, thus preventing damage to the uranium fuel rods and the reactor core and a corresponding release of radioactive materials. The ECCS will send water to cool the reactor in the event of a loss of coolant from the reactor cooling system. Immediately after an emergency shutdown, a forced flow of coolant (water) through the reactor core is required to rapidly remove the massive decay heat still emitted by the uranium fuel rods.

There are many variations of Emergency Core Cooling Systems (ECCS) in both the Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR) that now operate in the U.S. It is beyond the scope of this paper to provide detailed descriptions of all the variations of ECCS, however, it is possible to identify many of the components in these systems that (1) require electricity to operate, (2) depend upon solid state switches and control units to activate and control their operation (which are susceptible to high voltages and amperages generated by HEMP E1), and (3) which contain unshielded solid-state electronics and integrated circuits within their operating systems that can be disabled by HEMP E1. The loss of electric power and/or the loss of many components that comprise the ECCS will leave all but passive (mechanical, non-electrical) components of the ECCS inoperable – leaving the reactor quite vulnerable to destruction from the decay heat that remains in the core after emergency shutdown.

Motor-Driven Pumps in the ECCS (see diagrams in Appendix 3 for pump locations)

The NRC describes the ECCS as "Reactor system components (pumps, valves, heat exchangers, tanks, and piping) that are specifically designed to remove residual heat from the reactor fuel rods in the event of a failure of the normal core cooling system (reactor coolant system)."[195] Emergency makeup or cooling pumps are usually motor-driven. In Pressurized Water Reactors (PWR; 62 in operation in the U.S.[196]), the High Power Safety Injection (HPSI) System is used. The pumps used in the HPSI are primarily motor-driven and many of the valves in the system are motor-operated (Table 1).

Group	Description
AC Power	The ac buses and circuit breakers that supply power to the HPSI pumps.
Cooling	The pumps, valves, and heat exchangers that provide heat removal to the HPSI motor-driven pump and the HPSI room.
CVC Injection	The motor-operated valves and check valves in the HPSI injection path
CVC Pumps	All basic events associated with the CVC (charging; normally running) motor-driven pumps. The start, run, common-cause, and test and maintenance are included in the group of basic events.
DC Power	The batteries and battery chargers that supply power to the HPSI motor-driven pump control circuitry.
EPS	HPSI dependency on the emergency power system.
HPSI Injection	The motor-operated valves and check valves in the HPSI injection path.
HPSI Pumps	All basic events associated with the HPSI (generally lower head than CVC pumps; standby) motor-driven pumps. The start, run, common-cause, and test and maintenance are included in the group of basic events.
Special	Various events used in the models that are not directly associated with the HPSI system.
Suction	The motor-operated valves and air-operated valves in the tank suction path. Includes the failure of the tank.

Table 1: Motor-Driven Pumps and Motor-Operated Valves used in PWR HPSI Systems.[197]

[195] Nuclear Regulatory Commission. (March 9, 2021). "Emergency core cooling systems". https://www.nrc.gov/reading-rm/basic-ref/glossary/emergency-core-cooling-systems-eccs.html

[196] Nuclear Regulatory Commission. (Sept 21, 2022). "Power Reactors". https://www.nrc.gov/reactors/power.html

[197] Zhegang, M. Kellie, K. Schoeder, J. Wierman, T. (December 2019). "Safety Study: High Pressure Safety injection 1998-2018", Idaho National Laboratory, Department of Energy National Laboratory, Table 3. p. 9. https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_21672.pdf

Motor-driven pumps may contain unprotected solid-state circuits that could be damaged and disabled by HEMP E1. Motor-driven pumps are designed to receive power from diesel generators (or battery banks) if power is lost from the normal power supply.[198] Such pumps will not operate in the absence of electricity, and most (if not all) receive instructions via unshielded integrated circuits within a control system that could also be disabled by HEMP E1.

Low Pressure Pumps (2000 gpm)[199] are used in the Low Pressure Coolant Injection (LPCI) System found in BWR. The LPCI injects a coolant into the reactor vessel once it has been depressurized. Absence of electrical power and/or damage from E1 will disable Low and High Pressure Pumps along with the LPCI System.

Containment Spray Pumps used in the Containment Spray System (CSS) are mechanical pumps that don't require electricity to operate, however, the flow of spray from the pump is regulated and determined by temperature and pressure sensors,[200] which do contain integrated circuits that can be disabled by E1. Absence of electrical power and/or damage from E1 will disable the CSS. In some cases, steam turbine-driven pumps are used (e.g. in the case of BWR systems HPCI (High Pressure Coolant Injection).

Motor-Operated Valves in the ECCS (see Appendix 3)

Every nuclear power plant has thousands of valve actuators used in various processes and applications. The newest-generation nuclear plant has more than 13,000 valves within the

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[198] Op. cit. Nuclear Tourist. "Emergency Core Cooling Systems"
[199] Ibid.
[200] Nuclear Regulatory Commission. (October 2008). "Westinghouse Technology Systems Manual; Containment Spray Systems", USNRC Technical Training Center, USNRC HRTD, p. 11.4-3. https://www.nrc.gov/docs/ML1125/ML11251A035.pdf

plant,[201] and many types of them are motor-operated and located within the components that comprise the Emergency Core Cooling System[202] (see Appendix 3). Motor-operated valves require an electronic signal and electricity to open and close the valves that regulate the flow of cooling water. They will not function without electrical power or if their electronic controls have been destroyed by damaging voltages and currents induced by HEMP E1.

Pressure and Temperature Sensors

The host of electronic pressure, temperature, and water level sensors, which monitor the conditions within the reactor core and coolant systems, will not operate or send signals to the control room without electrical power. If their unshielded electronic components are damaged or destroyed by HEMP E1, they will be rendered inoperable even if power is available. Plant operators in the control room will not be able to monitor the water temperature or pressure in the Reactor Pressure Vessel. If it is possible to take manual measurements, plant personnel will have to be sent into the Primary Containment to do so and then return to the control room to report their findings if the plant communication system is not operational (no emergency power source and cell phones not working with the grid down).

Supervisory Control and Data Acquisition (SCADA) Control Units

All the various components that make up the emergency power and emergency cooling systems are regulated by at least one SCADA "Master Terminal Unit (MTU)", which is found in the instrument panels and automated controls located in the reactor control room (Figure 26). The MTU uses a communication system that is connected to data interface equipment, such as

[201] Kundin, P., "Actuation in Nuclear Power Plants", Valve Magazine, Oct 24, 2011, https://www.valvemagazine.com/articles/actuation-in-nuclear-power-plants
[202] Nuclear Regulatory Commission. (May 2010). "Theory of Operation of Motor-Operated Valves, Motor-Operated Course Manual, USNRC Technical Training Center. https://www.nrc.gov/docs/ML1134/ML11343A649.pdf

Programable Logic Controllers (PLCs) or remote terminal units (RTUs); these connect to pressure and temperature sensors, and water level sensors that monitor conditions in the reactor core.[203]

Figure 26: Kozloduy Nuclear Power Plant - Control Room of Units 3 and 4. Control features multiple consuls where data fed from SCADA systems is relayed to control room workers [204]

Unshielded SCADA MTUs, PLCs, and RTUs are all quite vulnerable to the high voltages and currents induced by HEMP E1. Should the SCADA unit(s) become inoperable, key functions such as pump regulation, turbine speeds, temperature control, temperature and pressure monitoring, and electrical output would become difficult, if not impossible to measure.[205]

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[203] Muthukrishnan, V. (April 4, 2021). "SCADA System: What is it?", Electrical 4U. https://www.electrical4u.com/scada-system/

[204] Kozloduy Nuclear Power Plant in Bulgaria., Control Room for Units 3 and 4 (1000 Mwe reactors) theywere shut down in 2007. https://commons.wikimedia.org/wiki/File:Kozloduy_Nuclear_Power_Plant_-_Control_Room_of_Units_3_and_4.jpg

[205] Op. cit. "EMP and Space Weather and the Strategic Threat to America's Nuclear Power Stations: 2015 Final Report", p. 24.

Passive (Non-Electric) Emergency Core Cooling Systems (ECCS)

Boiling Water Reactors

Passive systems, which are not dependent upon electrical power, are included the ECCS of all commercial nuclear reactor designs used in the United States. In 2022, there were 31 Boiling Water Reactors (BWR) operating in the US;[206] BWR use the High Pressure Coolant Injection (HPCI) System, which pushes water into the Reactor Pressure Vessel (while it is pressurized) using steam turbine-driven pumps.[207] The NRC writes that the HPCI system ". . . supplies adequate reactor vessel water inventory for core cooling on small break LOCA [Loss of Coolant Accident], assist in depressurization of the reactor vessel to allow the low pressure ECCS to inject on intermediate break LOCA, and backs up the Isolation Condenser or Reactor Core Isolation Cooling system under reactor isolation conditions."[208]

BWRs also have the Reactor Core Isolation Cooling (RCIC) System,[209] which is not considered part of the ECCS but is used during normal shutdown to supply the makeup water required to maintain reactor vessel inventory (the RICI does not have a loss of coolant accident (LOCA) function)[210]. The RCIC System was among a few of the safety systems that still could operate during the Fukushima Daiichi accidents after the tsunami hit the plants. The HPCI System was found to rapidly depressurize the primary system due to its large steam release rate

[206] Nuclear Regulatory Commission. (Sept 21, 2022). "Power Reactors". https://www.nrc.gov/reactors/power.html
[207] Nuclear Tourist. (Dec 8, 2005). "Emergency Core Cooling Systems". http://www.nucleartourist.com/systems/eccs.htm
[208] Nuclear Regulatory Commission, Reactor Training Branch. (July 2007). "Introduction to Reactor Technology – BWR, Part II, Chapter 10.0, Emergency Core Cooling Systems, p. 10-8. https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML12159A165
[209] Pressurized Water Reactors have an analogous system to the RCIC, which is a Turbine-Driven Auxiliary Feedwater Pump, which is used as a type of backup for water supply; it is not considered part of the ECCS. See Nuclear Regulatory Commission. (June 2003). "Westinghouse Technology Systems Manual, Section 5.7, Generic Auxiliary Feedwater Systems, USNRC Rev 0603, p. 5.7-3. https://www.nrc.gov/docs/ML1122/ML11223A229.pdf
[210] U.S. Nuclear Regulatory Commission. (October 24, 2022). "Reactor Core Isolation Cooling System". https://nrcoe.inl.gov/SysStudy/RCIC.aspx

(ten times higher than that of the RCIC System).[211] However, neither one of these systems was able to prevent the meltdown of Units 1, 2, and 3 following the loss of all emergency backup power, and subsequent failure of all the active ECCS, following the tsunami.[212]

Pressurized Water Reactors

Pressurized Water Reactors (PWRs) have an Auxiliary Feedwater System (AFS), which has both motor-driven and turbine-driven (use steam to drive pump, no electricity required) pumps that supply additional water to the coolant system in the event of a LOCA. However, the AFS does not feed into the reactor core, rather it supplies water to the steam generators, so it could not be used to create a forced flow through the reactor core after emergency shutdown.[213]

PWRs also have a passive system in their ECCS; the Cold-Leg Injection Accumulators, which consist of large volume tanks of borated water pressurized with nitrogen. (Borated water is used to absorb neutrons and thus will stop the fission process in the reactor core.) The Accumulator tanks ". . . are designed to provide water to the primary reactor coolant system during emergencies in which the pressure of the primary drops very rapidly, such as large primary breaks."[214] A large Loss of Coolant Accident (LOCA) is considered to be the most dangerous type of design-basis event, and the ECCS is geared towards managing this type of accident.

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[211] Gauntt, R., Kalinich, D., Cardoni, J., Phillips, J., Goldmann, A., Pickering, S., Francis, M., Robb, K., Ott, L., Wang, D., Smith, C., St.Germain, S., Schwieder, D., Phelan, C. (JULY 2021). "Fukushima Daiichi Accident Study (Status as of April 2012)", Sandia National Laboratories, p. 133. https://www.osti.gov/servlets/purl/1055601
[212] World Nuclear Association. (May 2022). "Fukushima Daiichi Accident". https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-daiichi-accident.aspx
[213] Poloski, J., Grant, G., Gentillion, C., Gaylearn, W., Knudsen, J. (May 1998). "Auxiliary/Feedwater System Reliability, 1987-1995, Idaho National Engineering and Environmental Laboratory, NUREG/CR-5500, INEEL/EXT-97-00740, Vol. 1. https://nrcoe.inl.gov/publicdocs/SystemStudies/nureg-cr-5500-vol-1.pdf
[214] USNRC Technical Training Center, (June 2003). "Pressurized Water Reactor (PWR) Systems, Reactor Concepts Manual", p. 4-24. https://www.nrc.gov/reading-rm/basic-ref/students/for-educators/04.pdf

However, the failure of emergency power and cooling systems following a HEMP will not likely include a LOCA, so it is not clear to me that the Accumulators would necessarily come into play. This is because a failure of the ECCS to deliver coolant to the reactor core would lead to rapid *increases* in temperature and pressure in the reactor core, rather than a drop in pressure in the primary coolant system, which the passive Accumulator system is designed to address.[215]

Emergency Shutdown Following HEMP

The EMP from a single high-altitude nuclear detonation (HEMP) would bring down most or all of the US national electric grid (see E3 HEMP). The loss of off-site power automatically triggers an emergency shutdown of a nuclear reactor. An emergency shutdown does not require electricity to occur in either Boiling Water Reactors (BWR) or Pressurized Water Reactors (PWR), which are the two types of Light Water Reactors used at U.S. nuclear power plants.[216] In a few seconds after an emergency shutdown is ordered, neutron-absorbing control rods are inserted into the reactor core;[217] this abruptly stops the process of nuclear fission occurring between the uranium fuel rods (nu clear fission, the splitting of uranium atoms, is the process that creates the immense amount of heat used to generate steam to produce electricity).[218]

When a commercial nuclear reactor is operating at full power, the primary reactor pumps typically push more than 4000 gallons of water per second through the Reactor Pressure

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[215] I have written to more than a dozen nuclear engineers (including those at 8 major universities) attempting to get answers to technical questions and have received no reply from any of them.

[216] Bays, S., Jayoude, D., Borlodan, G. (April 2019). "Reactor Fundamentals Handbook, Idaho National Laboratory, INL/EXT-19-53301, p. 56. https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_13579.pdf
Revision 0 https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_13579.pdf

[217] In some Boiling Water Reactors, control "blades" are inserted from below the core; the serve the same purpose as co the control rods. Britannica. (2023). "Reactor Control Elements". https://www.britannica.com/technology/nuclear-reactor/Fuel-types#ref155173

[218] A SCRAM event does not require electricity. Neutron absorbing control rods are held in place by electromagnets above the fissile pile and upon loss of electricity the electromagnets lose their magnetism, and the rods are dropped into place bringing fission to a near halt in the core. These systems are automated and do not require human intervention,

Vessel.[219] Pressurized Water Reactors can have two, three, or four primary pumps; these pumps can each pump 100,000 gallons of water per minute through the Reactor Pressure Vessel.[220] This enormous flow of water is required to remove the tremendous amount of heat produced by the nuclear fission in the reactor core (a 3400 MW thermal output reactor boils close to 36000 gallons of water per minute at full power).

Once the emergency shutdown takes place with the loss of off-site electrical power, the primary pumps stop. The primary reactor coolant pump or pumps cannot be restarted without the resumption of off-site power because their electrical requirements for restart are too large for on-site emergency power systems,[221] so the Emergency Core Cooling Systems (ECCS) are required to remove residual heat in the reactor core.

Station 1 Gert Hoffmeister, Germany [5]	Station 2 Derived with an allowance for warm to hot climates
Thermal Output 4000 MWt	Thermal Output 2000 MWt
Thermal to Electric Efficiency (Net) 35%	Thermal to Electric Efficiency (Net) 30%
Electrical Output 1400 MWe	Electrical Output 600 MWe
Decay Heat 6.5% of Full Power, 260 MWt initially	Decay Heat 6·5% of Full Power, 130 MWt initially
Decay Heat 1.5% of Full Power, 60 MWt 1 hour	Decay Heat 1·5% of Full Power, 30 MWt 1 hour
Decay Heat 0.5% of Full Power, 20 MWt 23 hours	Decay Heat 0·5% of Full Power, 10 MWt 23 hours
Decay Heat 0.2% of Full Power, 8 MWt 1 week	Decay Heat 0·2% of Full Power, 4 MWt 1 week

Table 2: Examples of Decay Heat in Nuclear Power Plants after a SCRAM/TRIP[222]

Even after the fission process is halted by the emergency shutdown, a huge amount of residual heat will remain within the reactor core. The extremely radioactive fission products within the uranium fuel rods will initially continue to produce 6% to 7% of the heat that the

[219] Rust, J., Weaver, L. (1976). *Nuclear Power Safety*, General Features of Emergency Core Cooling Systems, seehttps://www.sciencedirect.com/topics/engineering/core-cooling
[220] USNRC Technical Training Center, Reactor Concepts Manual. (June 2003). "Reactor Concepts Manual Pressurized Water Reactor Systems", p. 4-15. https://www.nrc.gov/docs/ML2005/ML20057E160.pdf
[221] Primary pumps in PWR range from 6,000 to 10,000 horsepower. USNRC Technical Training Center, Reactor Concepts Manual, "Reactor Concepts Manual Pressurized Water Reactor Systems", 0603, p. 4-15. https://www.nrc.gov/reading-rm/basic-ref/students/for-educators/04.pdf
[222] Clarke, M., (June 2020). "Battery Backups for Nuclear Power Plants" M.E.T.T.S. Consulting Engineers. http://www.metts.com.au/battery-backups-for-nuclear-power-plants.html

reactor normally generates while in operation (this is called "decay heat").[223] A typical commercial reactor that produces 4000 megawatts of heat, will consequently have about 260 million watts of decay heat being produced by the uranium fuel in its core following a SCRAM or TRIP (Table 2). Pressurized Water Reactors typically take 2 to 4 seconds to insert their control rods into the reactor core after a SCRAM.[224]

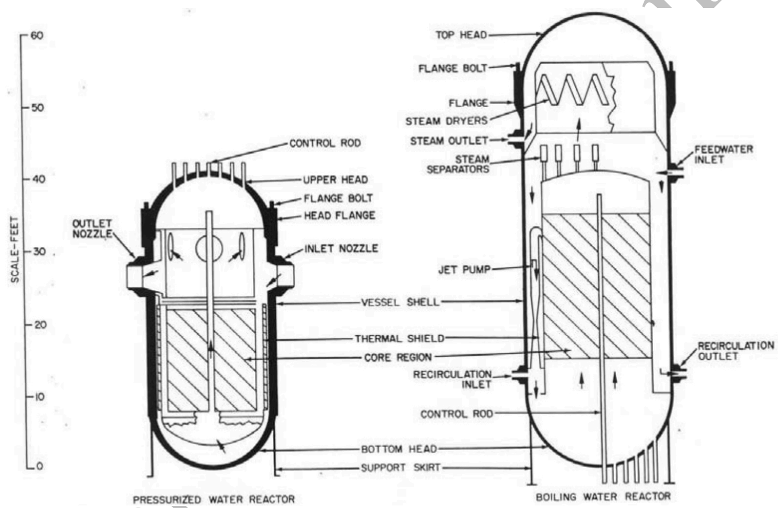

Figure 27: Comparative size of PWR and BWR Reactor Vessels.[225] In a BWR, there is normally about 16 feet of water above the reactor core,[226] which is approximately 40,000 gallons.

Hundreds of millions of watts of heat will then be trapped inside a cylindrical metal Reactor Pressure Vessel (RPV). In a Pressurized Water Reactor (PWR), the RPV may be about 43 feet tall with an internal diameter of 14 feet;[227] a Boiling Water Reactor (BWR) with approximately the same power output, will have a RPV that is around 60 feet tall (Figure 27).[228]

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[223] Nuclear Power. (2023). "SCRAM-Reactor Trip". https://www.nuclear-power.net/nuclear-power/reactor-physics/reactor-dynamics/scram-reactor-trip/
[224] Ibid.
[225] Ibid.
[226] https://blog.ucsusa.org/dlochbaum/reactor-core-cooling/
[227] U.S. Nuclear Regulatory Commission. (September 2009). "Westinghouse Technology Systems Manual. Section 3.1, Reactor Vessels and Internals", Table 3.1-1, p. 3.1-25. https://www.nrc.gov/docs/ML1122/ML11223A212.pdf
[228] International Atomic Energy Agency. (2009). "Integrity of Reactor Pressure Vessels in Nuclear Power Plants: Assessment of Irradiation Embrittlement Effects in Reactor Pressure Vessel Steels", IAEA Nuclear Energy Series, No. NP-T-3.1, Figure 6, p. 9. https://www-pub.iaea.org/MTCD/publications/PDF/Pub1382_web.pdf

This decay heat must be immediately and constantly removed from the core through the operation of the Emergency Core Cooling Systems (ECCS), otherwise the fuel in the core will rapidly overheat to the point of self-destruction.

In 2014, the Union of Concerned Scientists described the rate that water would boil-off in the core of a shutdown BWR when all cooling systems were not working. A week after the emergency shutdown, the decay heat from the reactor core would still boil water at the rate of 60 gallons per minute (Figure 28). If the cooling systems failed a week after shutdown (with the water level in the core at normal level) it would take only 11 hours for the water in the core to boil-off to the point where the top of the reactor core would be exposed to steam and air.[229] Nuclear fuel uncovered by water will rapidly heat up; when it reaches 1800°F, a chemical reaction between the metal cladding of the fuel rods and the steam flowing past will generate large quantities of hydrogen (this process is what led to the hydrogen explosions that destroyed the containment buildings at Fukushima Daiichi). The fuel rods will melt when they reach 2,200°F.[230]

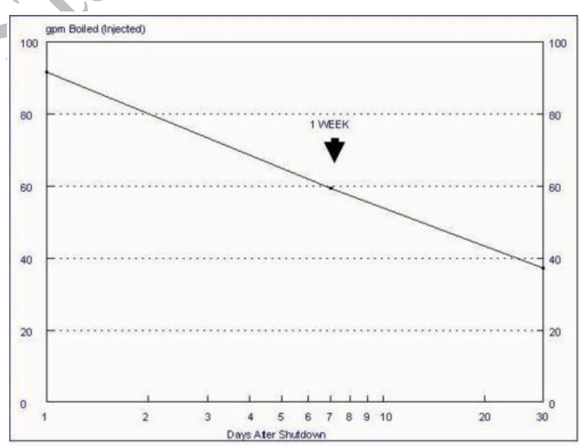

Figure 28: Rate of boil-off of coolant water in uncooled BWR core post shutdown[231]

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[229] Lochbaum, D. (March 14, 2011). "Reactor Core Cooling". https://blog.ucsusa.org/dlochbaum/reactor-core-cooling/

[230] Ibid.

[231] Ibid.

Events Following Emergency Shutdown Caused by HEMP

As previously mentioned, loss of off-site power triggers an emergency shutdown at nuclear power plants. If off-site power is suddenly lost, all the reactor primary coolant pumps automatically stop. The massive flywheels on the primary pumps will continue to turn and push a decreasing rate of flow through the reactor core (for example, in a large PWR with four primary reactor pumps, there will be 88% of full flow 5 seconds after the loss of off-site power; this process is called "flow coastdown").[232] [233] In smaller PWR that have fewer primary pumps, such as the AP600 with two pumps, the forced flow through the core will likely decrease at a faster rate.[234] The flow rate through the reactor will progressively decrease until in a matter of a minute or two it effectively ceases to provide any further cooling to the core.

Flow coastdown would provide some cooling to the core during short time when the ECCS are normally brought online following emergency shutdown. However, if the emergency power system fails, the motor-driven pumps within the active ECCS, which are required to move cooling water to and from the reactor core, will not operate. If emergency power is available, the pumps, as well as the SCADA systems in the control room that direct the operations of the active ECCS, may all have been disabled by effects of HEMP E1.

A failure of the active ECCS to operate will lead to the loss of forced core flow (coolant water being pumped through the reactor core), thereby causing a rapid increase in reactor coolant

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[232] Nuclear Regulatory Commission. (October 2008). "2.2 Reactor Coolant Pumps", p. 2.2-12. https://www.nrc.gov/docs/ML1125/ML11251A015.pdf

[233] There are more than 20 PWRs in the US that use 4 primary reactor pumps, see U.S. Nuclear Regulatory Commission. (June 2003). "Reactor Concepts Manual: Pressurized Water Reactor Systems", USNRC Technical Training Center, p. 4-6. https://www.nrc.gov/reading-rm/basic-ref/students/for-educators/04.pdf

[234] Nuclear Regulatory Commission. (March 16, 2000). "AP600 Design Control Document, Tier 2 Manual", Chapter 15, Figure 15.3.1-1, p. 15.3-15. https://www.nrc.gov/docs/ML0036/ML003691513.pdf

temperature.[235] This would leave only the passive systems, which do not require electricity, to deal with the massive decay heat remaining in the reactor core. These passive systems, in both Boiling Water Reactors and Pressurized Water Reactors, are not designed to pump coolant (water) directly into the core.

Complete Loss of Flow Accident (CLOFA) Caused by HEMP E1

A Loss of Flow Accident (LOFA) occurs when there is a reduction or cessation of coolant flow through the core of a nuclear reactor; it is a design-basis accident, meaning it is required by law to be considered in a reactor system's design.[236] A Complete Loss of Flow Accident (CLOFA), where there is a complete loss of forced coolant through the reactor core, is classified by the American Nuclear Society as a condition III event.[237] A CLOFA can result in damage to the fuel and ultimately the core, if forced coolant flow is not restored.

The conditions created by HEMP E1 – the loss of off-site power combined with the disabling of the emergency power systems and the active Emergency Core Cooling Systems (ECCS) – would create a condition that could be described as a CLOFA. Following the emergency shutdown and complete loss of all electrical power, neither the primary pumps, nor the secondary pumps in the ECCS could be used to remove heated water from the reactor core.

CLOFA in Boiling Water Reactors

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[235] Foad, B., Abdel-Latif, S., Toshikazu, T. (December 2018). "Reactivity feedback effect on loss of flow accident in PWR", Nuclear Engineering and Technology, Volume 50, Issue 8, pp. 1277-1288. https://www.sciencedirect.com/science/article/pii/S1738573317304448

[236] Luangdilok, W., Xu, P. (2020). "Chapter 5 – Nuclear plant severe accidents: challenges and prevention", *Advanced Security and Safeguarding in the Nuclear Industry*, pp. 99 – 134. https://www.sciencedirect.com/science/article/pii/B9780128182567000052

[237] Widodo, S., Ekariansyah, A., Tjahjono, H. (August 2016). "AP1000 Partial and Complete Loss of Flow Accidents Analysis Using RELAP5", National Technology Nuclear Seminar 2016, ISSN: 2355-7524. https://digilib.batan.go.id/e-prosiding/File%20Prosiding/Iptek%20Nuklir/SENTEN_2016/DATA/681_Surip%20Widodo.pdf

This type of condition has previously led to the meltdown of Boiling Water Reactors at Fukushima Daiichi in 2011. An earthquake caused the loss of off-site power, causing the nuclear reactors at Units 1, 2, and 3 to undergo emergency shutdowns; all three Units eventually lost all emergency power and subsequently lost the ability to move cooling water through their reactor cores. All three Units eventually had their reactor cores melt down as a result.

The EDGs and battery bank at Unit 1were both destroyed by the tsunami; the reactor core of Unit 1 melted down in about 7 hours after the loss of all electric power. Units 2 and 3 also lost their EDGs to the tsunami but they did have battery bank power for a limited amount of time until the batteries were exhausted. Both Units 2 and 3 subsequently had their nuclear reactors melt down within about 3 days following the tsunami.[238]

Units 1, 2, and 3 at Fukushima Daiichi were able to successfully conduct emergency shutdowns following the earthquake, which had caused the loss of off-site electrical power to the plant. These Units used their EDGs to begin the cooldown process of the reactor, which lasted about 49 to 51 minutes before two massive tsunamis arrived and destroyed all the EDGs.[239] During the cooldown period prior to the tsunami, the decay heat in their reactor cores decreased to about 2% of the pre-shutdown power level.[240] Yet this reduction of decay heat in their reactor cores did not prevent the reactors from self-destructing once all electric power was lost.

If nuclear power plants have their emergency power and/or emergency cooling systems disabled by HEMP E1, they will not be able use active ECCS to reduce the decay heat in the

[238] World Nuclear Association. (May 2022). “Fukushima Daiichi Accident”. https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-daiichi-accident.aspx
[239] Ibid.
[240] Decay heat will decrease to about 2% of the pre-shutdown power level within the first hour after shutdown and will decrease to 1% by the end of the first day post-shutdown; it will then continue to decrease, but it will decrease at a much slower rate and will be significant weeks and even months after the reactor is shutdown. U.S. Department of Energy. (June 1992). “DOE Fundamentals Handbook: Thermodynamics, Heat Transfer, and Fluid Flow," DOE-HDBK-1012/2-92. https://engineeringlibrary.org/reference/heat-transfer-decay-heat-doe-handbook

reactor core. In other words, plant operators will have at least 3 times more heat in the reactor cores to deal with than did the plant operators at Fukushima when they lost all electric power. U.S. Boiling Water Reactors, therefore, are likely to be highly susceptible to destruction from HEMP E1 if they remain unshielded from EMP.

CLOFA in Pressurized Water Reactors

An article published by the International Information System of the International Atomic Energy Agency states that a Loss of Flow Accident at a Pressurized Water Reactor will cause the reactor core to be "in a dangerous condition and the fuel elements will be damaged" if the reactor safety systems "do not work soon". The article states, "*The required protection is the reactor trip* [emergency shutdown] *followed by the adequate core cooling to remove residual heat and decay heat*."[241] If the emergency power systems and the motor-driven pumps are all left inoperable by the damage done by HEMP E1, the active ECCS systems will not be able to send cooling water to the core.

As previously mentioned, the passive ECCS system found in Pressurized Water Reactors – the Cold Leg Accumulator system – may not be automatically triggered in the event of a CLOFA caused by HEMP, because the Accumulators are designed to activate following a significant drop in pressure in the primary coolant system (following a LOCA). A failure of the Cold Leg Accumulators in PWRs to react to a CLOFA would mean that *none* of the ECCS systems in a PWR would come into play to restore forced flow of coolant through the reactor core.

[241] Suharno, I. (2007) "Core Cooling Mechanism on Loss of Flow Accident of PWR Power Reactor", International Atomic Energy Association, International Information System. https://inis.iaea.org/search/search.aspx?orig_q=RN:45006338

Events Leading to Core Meltdown following CLOFA caused by HEMP

Should emergency cooling systems fail to deliver cooling water to the reactor core after an emergency shutdown, the temperatures in the core will rapidly rise to the point where the fuel rods begin to degrade. Damage to the rods can begin to occur in as little as 30 minutes, or this may take as long as one to two hours.[242] A study done at Oak Ridge National Laboratory predicted that, without any power and without coolant injection into the reactor pressure vessel "fuel is uncovered in about half-an-hour, the core meltdown begins after two hours, and the drywell electrical penetration modules fail after 4.5 hours, venting radioactive noble gas, cesium, and iodine-based fission products into the reactor building".[243]

The Emergency Core Cooling Systems are designed to provide a number of pathways to send cooling water to the core inside the Reactor Pressure Vessel (RPV). If these Systems fail, the water that remains in the core after emergency shutdown will continue to heat and turn to steam until the top of the reactor core is no longer covered by water. The water level in the core will continue to drop as the exposed area of reactor core quickly superheats the steam and raises the pressure in the RPV so high that it will prevent the remaining water from boiling.

The fuel rods are normally at temperatures of less than 700°F (370°C) when a reactor is operating at full power. As the fuel rods heat up to 1,500 to 1,800°F, a chemical reaction between the Zircaloy cladding of the rods and the steam produces large amounts of hydrogen gas. [244] This process is what led to the hydrogen explosions that destroyed the secondary containment buildings at Fukushima Daiichi (Figure 29).

[242] Cook, D. Greene, S. Harrington, R. Hodge, S. Yue, D. (1981). "Station Blackout at Brown's Ferry Unit One – Accident Sequence Analysis", Oak Ridge National Laboratory, Prepared for the Nuclear Regulatory Commission, Table 9.7. https://www.slideshare.net/srgreene/nuregcr2182vol1
[243] Ibid.
[244] Lochbaum, D. (April 5, 2016). "Reactor Core Damage: Meltdown", Union of Concerned Scientists. https://blog.ucsusa.org/dlochbaum/reactor-core-damage-meltdown/

Figure 29: Fukushima Daiichi, Unit 3 after meltdown and hydrogen explosion[245]

Once the temperature of the fuel rods reaches 1,290-1650°F (700–900°C), the Zircaloy cladding of the rods will deform; if the pressure inside the RPV has been lowered through venting (via an emergency relief valve or pressure disc),[246] the internal pressure of the fuel rods will cause the Zircaloy cladding to rupture, and this will release highly radioactive gases from inside the rods. If the RPV has maintained high-pressure, the Zircaloy will remain on the rods and form a uranium dioxide-zirconium eutectic with a melting point of 1,200–1,400 °C (2,190–2,550 °F).

An exothermic reaction between steam and zirconium can also take place, which can become self-sustaining (a Zircaloy fire) that produces hydrogen. When temperatures in the core reach 1,300 to 1,500 °C (2,370 and 2,730 °F), the Zircaloy rod cladding evaporates. [247] When the

[245] IAEA Imagebank, CC BY-SA 2.0 <https://creativecommons.org/licenses/by-sa/2.0>, via Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Mike_Weightman_(02810459).jpg
[246] Steinkamp, H. (1995). "Emergency Venting of Pressure Vessels", International Atomic Energy Association, International Information System. https://inis.iaea.org/collection/NCLCollectionStore/_Public/28/005/28005402.pdf
[247] Libmann, J. (1996). "Elements of nuclear safety". L'Editeur : EDP Sciences. p. 194. ISBN 2-86883-286-5 and Kolev, N. (2009). "Multiphase Flow Dynamics 4: Nuclear Thermal Hydraulics", Volume 4. Springer. p. 501. ISBN 978-3-540-92917-8.

fuel rods reach the temperatures where they rupture or ignite, highly radioactive gases and fission products (iodine, krypton, and cesium) are released into the RPV. Virtually all the radioactive cesium in the rods will be converted to a gas,[248] which is why it becomes the predominant radioisotope in the fallout from catastrophic accidents at nuclear power plants where fuel rods are ruptured and/or ignited.[249]

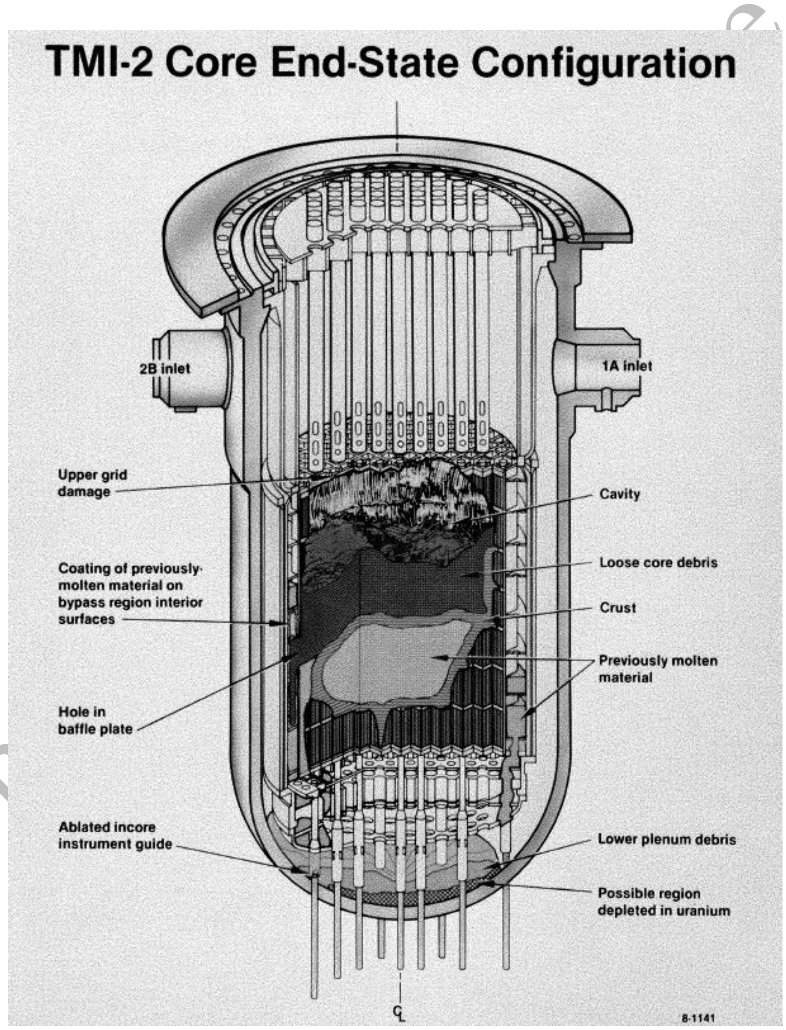

Figure 29: The meltdown of the Three Mile Island nuclear reactor destroyed the Reactor Pressure Vessel; the corium almost breached the Vessel and fell onto the containment floor below the reactor[250]

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[248] Cesium is the second most volatile element after mercury; it becomes a gas at 1240°F (671°C).

[249] Cesium-137, which has a 30-year half-life, appears in the key of maps that define the radiation control and exclusion zones of Chernobyl and Fukushima, see https://www.nature.com/articles/srep01742/figures/3 https://en.wikipedia.org/wiki/File:Chernobyl_radiation_map_1996.svg

[250] Op. cit. "Reactor Core Damage: Meltdown", Figure 4.

When temperatures in the core reach 2,700–2,800 °C (4,890–5,070 °F) the uranium oxide fuel rods melt and the reactor core structure collapses.[251] The lava-like molten uranium fuel, called "corium", will move to the bottom of the RPV (Figure 29). When the core of the reactors at Units 1, 2, and 3 in Fukushima Daiichi melted down, the corium broke through the bottom of the RPVs and then it destroyed the concrete beneath the RPV, allowing the radiation to reach the groundwater and then the Pacific Ocean (Figure 30).

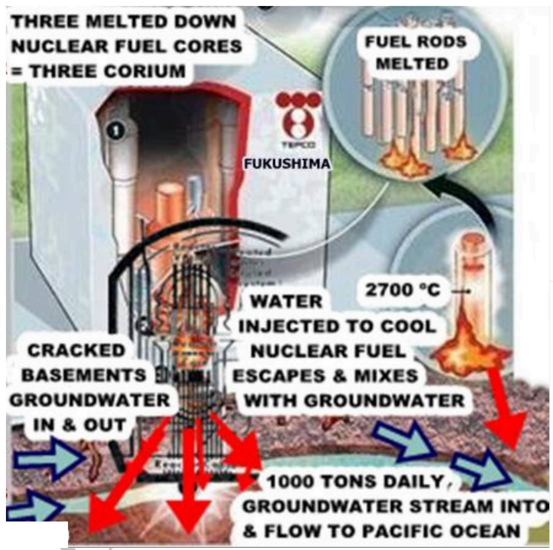

Figure 30: Illustration of Fukushima Daiichi melted cores forming corium, breaching the RPV, cracking concrete below, with radiation entering groundwater and Pacific Ocean.[252]

Vulnerabilities of Spent Fuel Pools to HEMP

High-level Radioactive Waste in Spent Fuel Pools

> *"If response organizations cannot provide timely support in terms of restoration of electrical power due to logistical interruption or issues with control systems (caused by EMS* [EMP and GMD] *impacts), in some cases, stations would have roughly 16 hours of battery power to continue cooling reactors and spent fuel pools.* ***In a worst-case scenario, all reactors within an affected region could be impacted***

[251] Op. cit. "Elements of nuclear safety"..
[252] Teres, F. (March 4, 2016)

> ***simultaneously. In the United States, this would risk meltdowns at approximately 60 sites and 99 nuclear reactors, with more than 60,000 metric tons of spent nuclear fuel in storage pools****. Prolonged loss of power to these critical sites poses a risk of radioactive contamination to the Continental United States with consequentially disastrous impact to the economy and public health."*
> – "Electromagnetic Task Force 2018 Report", US Air Force, Air University Press, Lemay Paper Number2, page 9[253]

Commercial nuclear reactors undergo refueling about every 12 to 18 months, when unused uranium fuel rods are loaded into the reactor core after the highly radioactive "spent fuel" is removed from the core (about one-third of the uranium rods in the reactor core are replaced). Unused uranium fuel rods can be handled without danger but spent fuel rods are intensely radioactive. Spent fuel gives off about 1 million rems (10,00Sv) of radiation per hour, which is enough radiation to kill a person who is next to the rods in a matter of seconds. For about the first 100 years, spent fuel emits gamma radiation at a dose rate greater than 1 sievert per hour, which would be lethal to about 50% of adults in three to four hours.[254]

During refueling operations, the intensely radioactive spent fuel is robotically removed from the top of the Reactor Pressure Vessel through a refueling cavity that is filled with water; the fuel is then transferred through water-filled transfer canals or tubes to at-reactor[255] spent fuel pools.[256] In U.S. Boiling Water Reactors, these pools are generally located within the reactor

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[253] Op. cit. Electromagnetic Defense Task Force (EDTF)", Air University Press Maxwell Air Force Base, Alabama, LeMay Paper No. 2.

[254] Alvarez, R. (May 2011). "Spent Nuclear Fuel Pools in the US: Reducing the Deadly Risks of Storage", Institute for Policy Studies, Washington D.C. Retrieved from https://www.nrc.gov/docs/ML1209/ML120970249.pdf

[255] There are also "away-from-reactor" spent fuel pools, which contain spent fuel that has significantly less radioactive and less thermally hot used fuel rods.

[256] Nuclear Energy Agency, Committee on the Safety of Nuclear Installations. (May 4, 2015). "Status Report on Spent Fuel Pools Under Loss-of-Cooling and Loss-of-Coolant Accident Conditions, Final Report", p. 32. https://www.oecd-nea.org/jcms/pl_19596/status-report-on-spent-fuel-pools-under-loss-of-cooling-and-loss-of-coolant-accident-conditions-final-report

building but outside primary containment; U.S. Pressurized Water Reactors also have their spent fuel pools located outside primary containment, but adjacent to it in a separate fuel handling building or auxiliary building.[257]

The pools are typically about 12 meters (36 feet) deep; they vary in width and length, depending on the reactor size, and are constructed of reinforced concrete with a stainless-steel liner to prevent leakage and maintain water quality. The fuel is stored in stainless steel racks that are submerged in about 7 meters (21 feet) of water.[258] Both the water in the pool and the thick concrete walls act to shield people from the intense radiation of the rods.

Spent fuel generates the most heat and radioactivity when it is first removed from the reactor core. The Nuclear Energy Agency states that "the maximum thermal power released from all spent fuel in the pool is typically about 0.3 % of the reactor thermal power (e.g., 10 MW for a 900 MWe reactor).[259] This heat will decrease with time, but it must be constantly cooled by a dedicated cooling system. The spent fuel cooling systems can accept backup emergency power from EDGs.[260] However, it is not clear if the EDGs at nuclear plants, which are designated to support the plant safety systems (ECCS, communication, and lighting systems, etc.), are now also designated to support the spent fuel pools. FLEX emergency diesel generators may have been given that assignment. It is not clear that all U.S. nuclear power plants store FLEX generators (and pumps) on-site, as there are regional storage centers set up to supply nuclear power plants within their defined service regions.

U.S. nuclear power plants store most of their spent fuel on-site. As of 2021, U.S. Department of Energy data showed that the U.S. had created close to 85,000 tons of spent

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[257] Ibid, p. 25.
[258] Ibid.
[259] Ibid, p. 21.
[260] Ibid, p. 34.

nuclear fuel.[261] Spent fuel must remain in the pool for 5 to 6 years (or longer for the "high-burnup" rods now in use) until its radioactivity and corresponding thermal heat declines enough to permit relatively safe removal from the pool and subsequent transport to interim storage (which typically is also on-site; the fuel assemblies are placed inside steel containers, which are welded shut and then encased in concrete, and placed above or below ground). About half of the total inventory of spent fuel remains in the pools, while the other half has been removed from the pools and placed in dry cask storage.[262]

Spent fuel pools were originally designed to hold slightly more than the contents of one reactor core's inventory, because there initially were no plans for long-term on-site storage.[263] A federal geologic long-term repository for the fuel was planned and built in Nevada, but attorneys representing Nevada claimed the site was poorly chosen due to "hydrology, inadequacy of the proposed waste package, repository design and volcanism",[264] and this political opposition prevented Yucca Mountain Nuclear Waste Repository from being opened. There were also plans to reprocess the spent fuel to extract plutonium, but concerns about nuclear weapons proliferation ended plans for reprocessing in 1977.[265]

Consequently, on-site spent fuel storage was expanded at the nuclear power plants by utilizing high-density storage in the fuel pools. All U.S. spent fuel pools now hold at least 3 to 5 times more radioactivity than is found in a reactor core (by 2013, some pools contained the

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261 Walton, R. (April 1, 2021). "Just the Stats: Volume of U.S. spent nuclear fuel totals 85K metric tons since 1968", Power Engineering. https://www.power-eng.com/nuclear/just-the-stats-volume-of-u-s-spent-nuclear-totals-85k-metric-tons-since-1968/#gref

262 Alvarez, R. (November 13, 2020). "What Congress Needs to Know About Pending Nuclear Waste Legislation", Environmental and Energy Study Institute. https://www.eesi.org/briefings/view/111320nuclear

263 Kadak, A. (June 15, 2012). "Storage of Spent Nuclear Fuel, National Academy of Engineering. https://www.nae.edu/59226/Storage-of-Spent-Nuclear-Fuel

264 State of Nevada. (2023). "The Fight Against Yucca Mountain". https://ag.nv.gov/Hot_Topics/Issue/Yucca/

265 Walsh, E. (April 8, 1977). "Carter Acts to Curb the Spread of Plutonium", The Washington Post. https://www.washingtonpost.com/archive/politics/1977/04/08/carter-acts-to-curb-spread-of-plutonium/ef0ef035-b6e6-4b90-94e3-c3109d2692eb/

equivalent of nearly 9 reactor cores of spent fuel).[266] The greatly increased density of the fuel in the pools makes it impossible to cool the fuel by natural circulation of the water, which means pool cooling systems have to be kept running constantly to prevent overheating of the pools.

These pools represent some of the highest concentrations of radioactivity on the planet.[267] Roughly 40% of the total radioactivity in spent fuel is emitted by cesium-137 – a highly radioactive fission product with a 30-year half-life.[268] Cesium-137 appears to be the primary long-term environmental contaminant from the meltdown of the nuclear reactors at the Chernobyl and Fukushima nuclear power plants;[269] tens of thousands of square miles became radiation control zones, and about 2827 square kilometers (1100 square miles) remain an uninhabitable radiation exclusion zone from the Chernobyl disaster.

The key within the 1996 map of the destroyed Chernobyl nuclear plant (Figure 32) shows that the contamination of a square kilometer of land with 40 Curies of cesium-137 is what qualifies that land to be classified as an uninhabitable closed/exclusion zone. There are 88 Curies *per gram* of cesium-137, so less than half a gram of cesium-137, made into an aerosol and distributed over a square kilometer (1.2 grams per square mile), will leave that land uninhabitable for at least a century.[270] 1.2 grams is less than half the weight of a U.S. dime.

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[266] Statement of David Lochbaum, Director, Nuclear Safety Project, Before the Senate Committee on Energy and Natural Resources. (July 20, 2013). https://www.energy.senate.gov/services/files/89dbc888-171c-4f77-8ecf-83a0055fcfb9

[267] Op. cit. "Spent Nuclear Fuel Pools in the US: Reducing the Deadly Risks of Storage"

[268] Op. cit. "What Congress Needs to Know About Pending Nuclear Waste Legislation"

[269] The water-soluble form of cesium becomes ubiquitous in contaminated ecosystems and is recycled by plants and animals because it is in the same atomic family as potassium, which is a macronutrient.

[270] Cesium-137 has a 30-year half-life; after 10 half-lives, about 1/1000 of the original total would remain.

Figure 32: Map of Chernobyl Radiation Control and Closed Zones in 1996[271]

The fuel rods in each U.S. spent fuel pool contain hundreds of kilograms/pounds of cesium-137. The Chernobyl incident did not involve a spent fuel pool; it was the reactor that exploded, which released cesium-137 inventories with 1.89 million curies of radiation. This left an area half the size of New Jersey uninhabitable. In comparison, Unit 3 of the closed San Onofre Nuclear Power Plant in San Diego contains cesium-137 inventories amounting to 61.6 million curies of radiation – more than 30 times cesium-137 released by Chernobyl.[272]

[271] CIA Factbook, Sting (vectorisation), MTruch (English translation), Makeemlighter (English translation) - http://www.lib.utexas.edu/maps/belarus.html, specifically http://www.lib.utexas.edu/maps/commonwealth/chornobyl_radiation96.jpg and File:Tchernobyl_radiation_1996.svg for the vector version, CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=2628661

[272] Op. cit. "Spent Nuclear Fuel Pools in the US: Reducing the Deadly Risks of Storage"

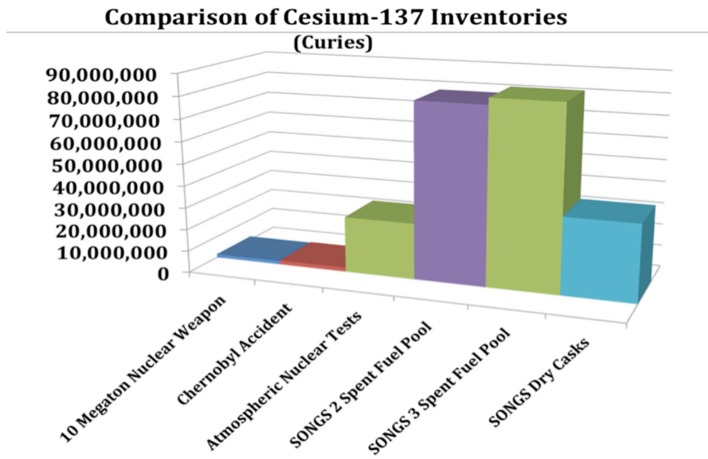

Figure 33: Cesium-137 in individual spent fuel pools 2 and 3 at San Onofre Nuclear Generating Station (SONGS). SONGS 2 and SONGS 3 Spent Fuel Pools contained 89 times more cesium-137 than was released by the exploded Chernobyl reactor.[273]

Vulnerabilities of Spent Fuel Pools to Long-term Loss of Power

Should HEMP bring down the national electric grid, nuclear power plants would be left without off-site electrical power, which they require to continuously operate the cooling systems used to cool their spent fuel pools. If emergency power systems at the nuclear plant are damaged by HEMP and fail to operate, the large amounts of heat given off by the spent fuel will, in a matter of days or weeks, cause the water in the pools to heat to the point of boiling – unless water can be pumped back into the pools on a routine basis. This would require working (undamaged) diesel generators, pumps and a supply of diesel fuel that perhaps would need to be sufficient to pump water into the spent fuel pools for months. If FLEX equipment is kept on-site, it may include pumps that can be used to pump water into the spent fuel pools.

Nuclear power plants are currently required to store only a week's worth of diesel fuel on site, and this is for the purpose of running the emergency diesel generators to power the plant

[273] Alvarez, R. (June 25, 2013). "Reducing the hazards of high-level radioactive waste in Southern California: Storage of spent nuclear fuel at San Onofre", Friends of the Earth, p. 4. https://sanonofresafety.files.wordpress.com/2018/06/songs_spent_fuel_final-alvarez.pdf

lighting, communication systems, and emergency core cooling systems needed to safely cooldown the reactor core.[274] In 2018, a report from the U.S. Air Force Air Academy warned that "Extended electrical power loss to nuclear power plants can lead to widespread radioactive contamination from the overheating of on-site spent fuel pools and breach of reactor containment at more than 60 sites and affect US military installations."[275] To reduce this danger, the report recommended that EMP-hardened generators and at least 30 days' worth of additional fuel (on-site) be supplied for the generators, in conjunction with the transferring of spent fuel to dry cask storage.[276]

Consequences of Loss of Cooling in Spent Fuel Pools

If HEMP should knock out the US national electric grid and disable the emergency power systems at a nuclear power plant, in a matter of hours or days, the water in the spent fuel pool will heat to the point of boiling.[277] The water in the pool will then "boil-off", exposing the spent fuel rods to steam and water.[278] Exposure to steam or air would cause the zirconium alloy cladding on rods to heat to the point of rupture, which would allow the release of radioactive gases (primarily radioactive cesium). U.S. spent fuel pool are densely packed with spent fuel rods, making them quite susceptible to spent fuel pool fires. If the pool contains fuel rods that have been removed from the core during the previous six to twelve months, the exposed rods

[274] Nuclear Regulatory Commission, REGULATORY GUIDE 1.137 (July 2012). "Fuel Oil Systems for Emergency Power Supplies". https://www.nrc.gov/docs/ML1230/ML12300A122.pdf
[275] Stuckenberg, D., Woolsey, J., DeMaio, D. (November 2018). "Electromagnetic Defense Task Force (EDTF)", Air University Press Maxwell Air Force Base, Alabama, LeMay Paper No. 2, p. 32. https://www.airuniversity.af.edu/Portals/10/AUPress/Papers/LP_0002_DeMaio_Electromagnetic_Defense_Task_Force.pdf
[276] Ibid
[277] 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
[278] 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.

may heat to the point of ignition,[279] leading to a propagating fuel rod fire that would involve all the rods the pool.[280]

In 2003, a peer-reviewed article, published by the international journal *Science and Global Security*, described the dangers of "dense-packed" spent fuel:

> "It has been known for more than two decades that, in case of a loss of water in the pool, convective air cooling would be relatively ineffective in such a "dense-packed" pool. Spent fuel recently discharged from a reactor could heat up relatively rapidly to temperatures at which the zircaloy fuel cladding could catch fire and the fuel's volatile fission products, including 30-year half-life 137Cs, would be released. The fire could well spread to older spent fuel. The long-term land-contamination consequences of such an event could be significantly worse than those from Chernobyl."[281]

U.S. spent fuel pools are located *outside* of the primary containment that houses the nuclear reactor (unlike Russian nuclear power plants), so they do *not* have a steel-lined, concrete barrier that covers reactor vessels to prevent the escape of radioactivity. Many of the secondary containment buildings for spent fuel are not robust structures. A single spent pool fire could release huge amounts of radiation that could leave tens of thousands of square miles uninhabitable for a century or longer.[282] [283] *Dozens of spent fuel pool fires – created by a single HEMP – could leave much or most of the U.S. uninhabitable*.

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[279]Rods more recently removed from the reactor – within 6 to 12 months – produce enough heat from radioactive decay to ignite a strongly exothermic reaction if exposed to steam or air, which burns at temperatures of thousands of degrees F and spread throughout the pool, see Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report (2006), National Academies of Sciences, pp. 38-39, see http://nap.edu/11263

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

[281] 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, pp. 1-2. https://www.nrc.gov/docs/ML1209/ML120960695.pdf

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

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

Reduce the Danger of Catastrophic Release of Radiation from Spent Fuel Pools

The danger posed by the destruction of spent fuel pools could be significantly reduced by removing most of the spent fuel from the pools and placing it in thick-metal casks for interim dry cask storage. The U.S. Air Force Air Academy published a study that showed the importance of using dry cask storage by calculating the effects of the destructions of U.S. spent fuel pools following HEMP. Figure 36 is taken from that study; it shows dry cask storage could prevent the radioactive contamination of more than 93,000 square miles of U.S. land and thus prevent the displacement of more than 3 million Americans.

Comparison of Spent Fuel Storage Impacts (unspecified cooling loss)		
Impacts	Spent Fuel Pool Storage	Dry Cask Storage
Population Displaced	4,100,000	800,000
Landmass Contamination	94,000 sq. miles	170 sq. miles
Radioactive Contaminates Released	8.8 MCI of Ce-137	.8 MCI of Ce-137

Sources: National Academy of Sciences, "Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants Phase 2," 2016, based on data from the Nuclear Regulatory Commission, NUREG-2161, "Consequence Study of Beyond-Design Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boling Water Reactor," September 2014.

Figure 36: Removing spent nuclear fuel from fuel pools and putting it into dry cask storage could greatly reduce displaced populations in a worst-case scenario with U.S spent fuel pools losing the ability to keep spent fuel cool[284]

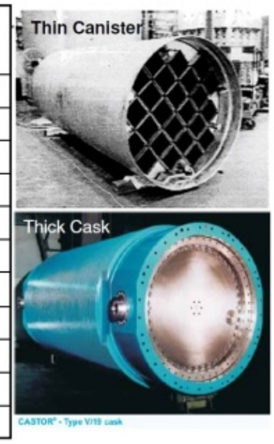
Once spent fuel has remained in the pool long enough to cool enough to permit its removal (radiation and heat levels must be reduced to specific levels), it can be removed from the pool. By November 2020, U.S. nuclear power plants had removed 48% of its spent fuel from spent fuel pools,[285]while about half remained in the pools. Most of the spent fuel removed from

[284] Op. cit. "Electromagnetic Defense Task Force (EDTF)", p. 13.
[285] Op. cit. "Spent Nuclear Fuel Pools in the US: Reducing the Deadly Risks of Storage"

the pools was stored in thin-metal canisters (which is put into large metal-lined concrete casks that reduce exposure to radiation and allow passive cooling).

Ten reasons to use thick nuclear waste storage casks

Safety Features	Thin canisters	Thick casks
1. Thick walls	1/2”- 5/8”	10”- 19.75”
2. Won’t crack		√
3. Ability to repair, replace seals		√
4. Ability to inspect (inside & out)		√
5. Monitor system prevents leaks		√
6. ASME container certification		√
7. Defense in depth (redundancy)		√
8. Store in concrete building		√
9. Gamma & neutron protection	Need overpack	√
10. Transportable w/o add’l cask		√
Market leader	U.S.	World



SanOnofreSafety.org

Figure 34: Comparison of thin-metal canisters to thick-metal casks for storage of spent nuclear fuel[286]

Unfortunately, the austenitic stainless steels used in thin-metal canisters are known to be susceptible to corrosion and cracking,[287] which can begin internally and is not detectable from outside the canister (inspection is made impossible because the canisters are placed in large metal-lined concrete casks). The internal pressure of the thin-metal canisters cannot be monitored; internal pressure can be monitored with thick-metal casks, which are routinely used outside the U.S. for interim storage.[288] Spent fuel is not retrievable with thin-metal canisters (lids

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[286] Gilmore, D. (2023). San Onofre Safety. https://sanonofresafety.org/

[287] “When austenitic stainless steel is welded, the weld metal itself is melted and homogenized. However, with the heat-affected zone (HAZ) near the weld, the steel becomes sensitized. When the metal is heated during the welding process, Cr diffuses from the metal grains into the grain boundaries, where it combines with carbon to form chromium carbides. Sensitization results in the formation of chromium depleted zones at grain boundaries that facilitate the nucleation and propagation of localized corrosion such as pitting (often a precursor for SCC) and SCC [Stress, Cracking, and Corrosion].” Ilgen, A., Bryan, C., Hardin, E. (March 25, 2015). “Draft Geologic Disposal Requirements Basis for STAD Specification”, Prepared for U.S. Department of Energy Nuclear Fuels Storage and Transportation Planning Project, Sandia National Laboratories, pp. 29-30. https://www.nrc.gov/docs/ML1613/ML16132A321.pdf

[288] Thin-metal canisters also have to be loaded into metal-lined concrete containers and during the loading process, it is virtually impossible to prevent some contact of the stainless-steel canister with the metal liner, which has the potential to accelerate corrosion and cracking (the concrete containers are necessary to protect workers from

welded on) but is retrievable with thick-metal casks (lids bolted on). Thin-metal canisters were intended for short-term storage and will have to be repackaged,[289] which hopefully will be in the superior thick-metal casks.

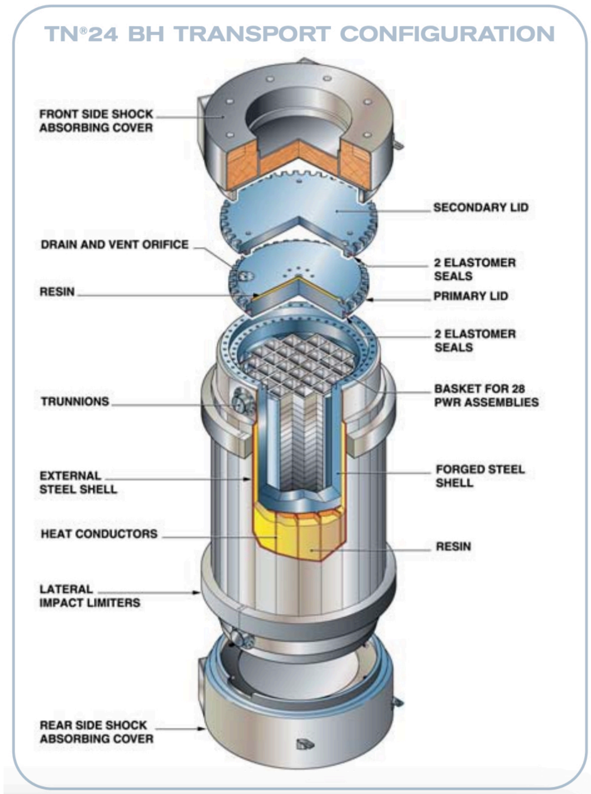

Figure 35: Areva TN 24 BH Thick-metal cask that holds 69 BWR fuel assemblies for interim storage[290](there are 74 to 100 fuel rods in each BWR fuel assembly)

As of 2019, there was $40.9 billion in the Nuclear Waste Fund (collected from U.S. rate payers), which was meant to finance the disposal of spent nuclear fuel. However, U.S. Federal law must first be revised to allow these funds to be used for the removal and storage of spent fuel

radiation emitted by the fuel; concrete containers are not necessary with thick-metal casks which sufficiently block the radiation).

289 Op. cit. "What Congress Needs to Know About Pending Nuclear Waste Legislation"

290 Areva TN. (July 2013). "Metal Casks for Used Fuel Transport and Storage". https://sanonofresafety.files.wordpress.com/2013/06/2013-10-01-2_tn24-a-rc3a9viser_v7.pdf

from spent fuel pools.[291] Under the Nuclear Waste Policy Act, the U.S. government cannot accept legal responsibility for spent nuclear fuel until it is received at an open repository site (the funds cannot currently be used for on-site storage). A federal court stopped reactor operator payments to the fund in 2014, because no repository site had been opened (the law required that one be opened by January 31, 1998).

The removal of spent fuel from the pools could also facilitate the use of low-density storage techniques within the pools, which the pools were originally designed to use. If the loss water from the pool leads to the exposure of spent fuel rods, low-density storage allows the natural convection of water and steam to circulate between the racks holding the fuel, which would provide a significant cooling process not currently possible in U.S. spent fuel pools.[292] In order to prevent spent fuel from becoming critical (starting a fission process between the rods crowded into the pool), today's pools use plates containing neutron-absorbing material to separate the rods.[293] These plates allow many more rods to be stored in the spent fuel pools, but the plates significantly reduce the flow of water through the pool.

Shield 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

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[291] The *Nuclear Waste Policy Act* stipulates these funds can only be used for the permanent disposal of waste. Costs for consolidated interim storage sites are not borne by the U.S. government, unless title is transferred by amending the *Nuclear Waste Policy Act.* https://www.eesi.org/briefings/view/111320nuclear An amendment was attempted in 2019 but was not voted on. https://www.govtrack.us/congress/bills/116/hr2699

[292] Thompson, G. (January 31, 2013). "Handbook to Support Assessment of Radiological Risk Arising from Management of Spent Nuclear Fuel", Nautilus Institute for Security and Sustainability, p. 19. https://nautilus.org/napsnet/napsnet-special-reports/handbook-to-support-assessment-of-radiological-risk-arising-from-management-of-spent-nuclear-fuel/

[293] Ibid, p. 20.

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.[294] [295] [296]

Unfortunately, the Nuclear Regulatory Commission continues to regard nuclear power plants as being immune to HEMP. Consequently, the citizens of the U.S.A. – as well as those persons residing in nations that have not protected their national electric grid and nuclear power plants[297] – remain very much at risk from the catastrophic effects of HEMP.[298]

[294] 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
[295] Op. cit. Radasky, "Protecting Industry from HEMP and IEMI"
[296] 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
[297] France could see more than 50 nuclear reactors simultaneously meltdown from a single HEMP.
[298] Op. cit. "Low-Frequency Protection Concepts for the Electric Power Grid".

Postscript

Today, in 2023, there are more than 12,000 nuclear weapons in the arsenals of the nuclear weapon states (the U.S. and Russia own 93% of them). Ideally, the abolition of nuclear weapons would virtually eliminate the danger of HEMP, however, it appears humanity is not on the verge of making such a decision. And since a single nuclear detonation – or a massive Geomagnetic Disturbance – can bring down the currently unshielded U.S. national electric grid, it seems necessary to take action to protect the grid and critical national infrastructure from HEMP.

Even if nuclear power plants were all to shut down and stop the production of spent nuclear fuel, there are still more than 85,000 tons of spent fuel stored on-site at U.S. nuclear power plants[299] (and more than 400,000 tons of spent fuel stored above ground at hundreds of sites around the world[300]). But it also seems unlikely that the U.S. will soon forgo the use of nuclear power, which currently increases the U.S. total of spent fuel by about 2,000 tons a year.[301] The best interim solution to spent fuel is to remove most of it from the spent fuel pools (the fuel that has been in the pools long enough to be safely removed) and place it in thick-metal casks for monitored storage in hardened facilities. The debate about geologic long-term storage is not yet settled,[302] so it appears that a truly safe long-term solution, which will prevent this highly radioactive waste from getting loose in the biosphere, has yet to be determined.

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299 Walton, R. (April 1, 2021). "Just the Stats: Volume of U.S. spent nuclear fuel totals 85K metric tons since 1968", Power Engineering. https://www.power-eng.com/nuclear/just-the-stats-volume-of-u-s-spent-nuclear-totals-85k-metric-tons-since-1968/#gref

300 Le. T. (June 17, 2020). "Spent Nuclear Fuel Storage and Disposal", Nonproliferation. https://www.stimson.org/2020/spent-nuclear-fuel-storage-and-disposal/

301 U.S. Department of Energy. (October 3, 2022). "5 Fast Facts About Spent Fuel", Office of Nuclear Energy. https://www.energy.gov/ne/articles/5-fast-facts-about-spent-nuclear-fuel

302 In 2018, the U.S. Nuclear Waste Technical Review Board (NWTRB) admitted no country has short-term storage and monitoring technology solutions needed to implement a safe permanent geological repository, stating "Long-term research, development, and demonstration of monitoring and sensor technologies are needed to address *current technology limitations***.**" U.S. Nuclear Waste Technical Review Board. (May 2018). "Geologic Repositories: Performance Monitoring and Retrievability of Emplaced High-Level Radioactive Waste and Spent Nuclear Fuel", p. iv. https://www.nwtrb.gov/docs/default-source/reports/nwtrb_perfmonitoring.pdf?sfvrsn=6

Author's note on Intentional Electromagnetic Interference (IEMI) devices

There are small portable Intentional Electromagnetic Interference (IEMI) devices, which can be used as powerful electromagnetic weapons at short ranges. Such IEMI devices could be used to cripple components of critical national infrastructure – including nuclear power plants. This paper will focus on the effects of an Electromagnetic Pulse (EMP) created by a high-altitude nuclear detonation (HEMP), however, details on IEMI can be found in the publications of the Metatech Corporation and Dr. William Radasky.[303] [304] The protective measures described in the paper for HEMP also apply for the EMP created by IEMI devices.

[303] Radasky, W. (October 31, 2018). "Protecting Industry from HEMP and IEMI", *In Compliance Magazine.* https://incompliancemag.com/article/protecting-industry-from-hemp-and-iemi/

[304] Radasky, W., Savage, E. (Jan 2010). "Intentional Electromagnetic Interference (IEMI) and Its Impact on the U.S. Power Grid ", Metatech Corp, Meta-R-323. https://www.futurescience.com/emp/ferc_Meta-R-323.pdf

Appendix 1: Solid State Electronics Susceptible to High Voltage, High-voltage substations, Insulators on Distribution Powerlines

All Figures are in Appendix 1 are from "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid" and the original Figure numbers are retained with the images.

Savage, Edward, James Gilbert, and William Radasky. (2010). "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid". Metatech Corporation, Meta R-320. https://www.futurescience.com/emp/ferc_Meta-R-320.pdf

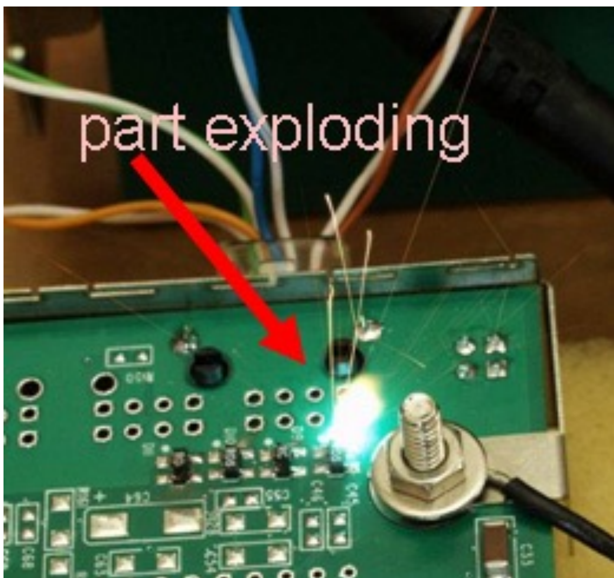

Figure 6-1. A part (a resistor) exploding under pulse testing, p. 6-1

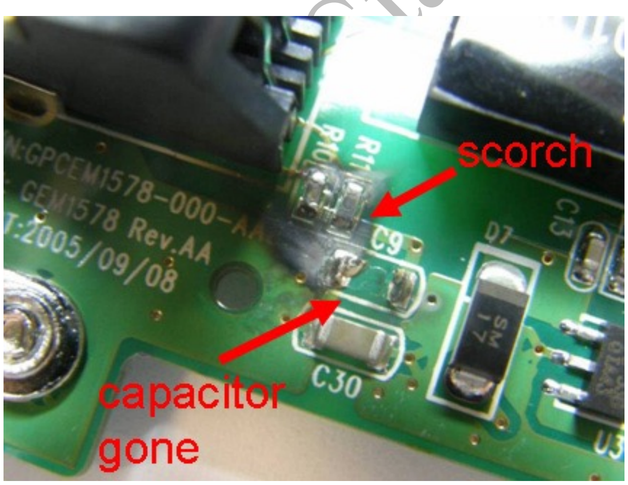

Figure 6-2. Capacitor damage from pulse testing. The capacitor (C9) is gone, and there are scorch marks (C30 shows an undamaged capacitor), p. 6-2

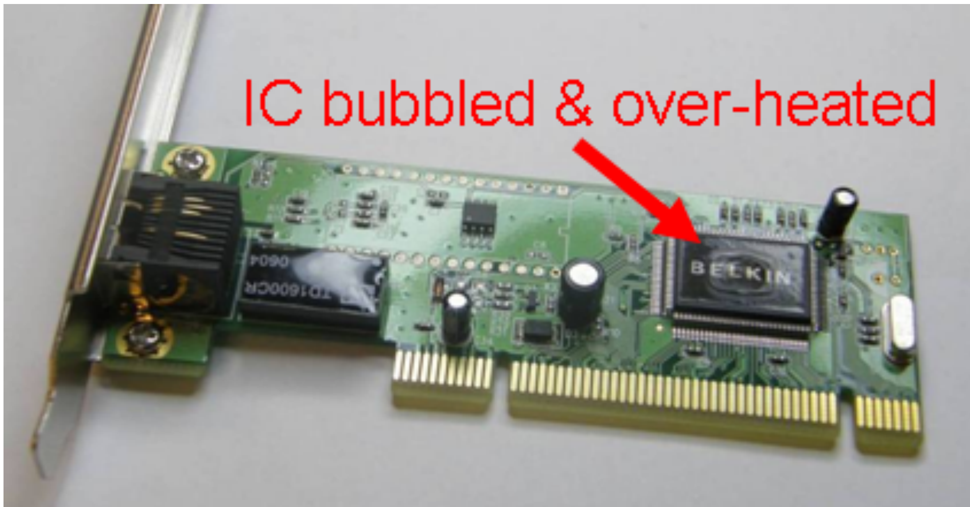

Figure 6-3. The result of pulse testing – IC damage. The IC lid, normally flat, has bubbled, and is discolored from over-heating, p. 6-2

Figure 6-7. Arcing at the port to a system. This is computer network card, with the arcing in the connector where the network cable plugs in, p. 6-10

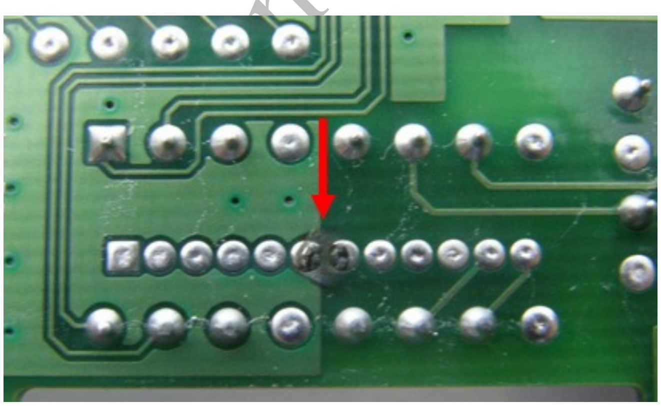

Figure 6-8. Signs of arcing between solder pads on a circuit card, p. 6-10

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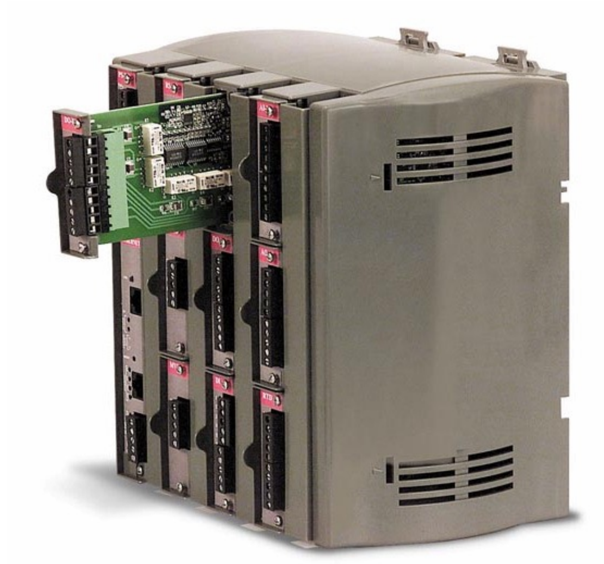


Figure 7-14. The Fisher ROC809 Remote Operations Controller. This is a PLC, such as might be used for remote controlling of a pipeline. It has a computer, and then may be configured with various I/O units: analog, binary, and communications. P. 7-16

Fisher ROC809 unit: Damage was as low as 1 kV for the analog out port, (at 1 kV) the level was too high, and it no longer would work. The Ethernet port was upset at 3 kV, and damaged at 4.5 kV.

Table 7-5. Fast pulse results for the Fisher ROC809 unit, p. 7-17

Fisher ROC809 Remote Operations Controller					
DUT		Drive	Voltage Level: Charge/Load, kV		
Unit	Port		No Effect	Upset	Damage
ROC809	Discrete In	Differential	-	3.0/3.4	-
	Discrete Out	Differential	-	8.0/5.2	
	Analog In	Differential	8.0/4.5	-	-
	Analog Out	Differential	-	-	1.0/0.6
	Serial Port	Common	-	-	2.5/2.1
	Ethernet	Common	-	3.0/3.0	4.5/4.7
Power Supply	AC In	Differential	8.0/5.1	-	-
Breadth of Effect:	Pulsed Port		Associated Ports		System Wide

Figure 7-15. The Allen-Bradley MicroLogix 1000 PLC. The PLC, the unit on the right, has analog and binary I/O ports. Its communications is handled by the 1761-NET-ENI unit shown on the left, p. 7-17

Table 7-6. Fast pulse results for the Allen-Bradley MicroLogix 1000 PLC, p. 7-18

Allen-Bradley MicroLogix 1000 PLC					
DUT		Drive	Voltage Level: Charge/Load, kV		
Unit	Port		No Effect	Upset	Damage
MicroLogix 1000 PLC	Discrete In AC	Differential	8.0/7.1	-	-
	Discrete In DC	Differential	-	8.0/6.2	-
		Common	-	4.5/1.6	-
	Discrete Out	Differential	8.0/6.1	-	-
	Analog In, V	Differential	-	-	3.5/3.3
	Analog In, I	Differential	-	2.5/1.7	-
	Analog Out, V	Differential	4.5/2.0	-	-
	Serial Port	Common	-	7.0/5.9	-
	AC power	Differential	8.0/5.0	-	-
ENI	Ethernet	Common	-	4.5/3.9	2*3.5/4.0
Breadth of Effect:	Pulsed Port		Associated Ports		System Wide

Table 7-7. Slow pulse results for the Allen-Bradley MicroLogix 1000 PLC.(only a few ports were tested), p. 7-18

Allen-Bradley MicroLogix 1000 PLC, CWG Pulse					
DUT		Drive	Voltage Level: Charge/Load, kV		
Unit	Port		No Effect	Upset	Damage
MicroLogix 1000 PLC	Discrete In AC	Differential	-	-	4.0/4.0
	Analog Out, V	Differential	-	-	0.6/0.6
Breadth of Effect:	Pulsed Port		Associated Ports		System Wide

Table 7-8. Fast pulse results for a typical PC and network switch, p. 7-19

Compaq PC					
DUT		Drive	Voltage Level: Charge/Load, kV		
Unit	Port		No Effect	Upset	Damage
Network Switch	Downlinks	Common	-	2.5/2.3	-
	Uplink	Common	-	2.0/2.0	-
	AC Power	Differential	8.0/6.8	-	-
PC	LAN PC Card	Common	-	4.5/3.8	-
	Onboard LAN	Common	-	5.0/2.4	-
	Modem	Common	8.0/4.3	-	-
	Serial Port	Common	-	-	0.75/0.5
	AC power	Differential	8.0/5.1	-	-
Breadth of Effect:	Pulsed Port	Associated Ports	System Wide		

E1 HEMP concerns within a high voltage substation

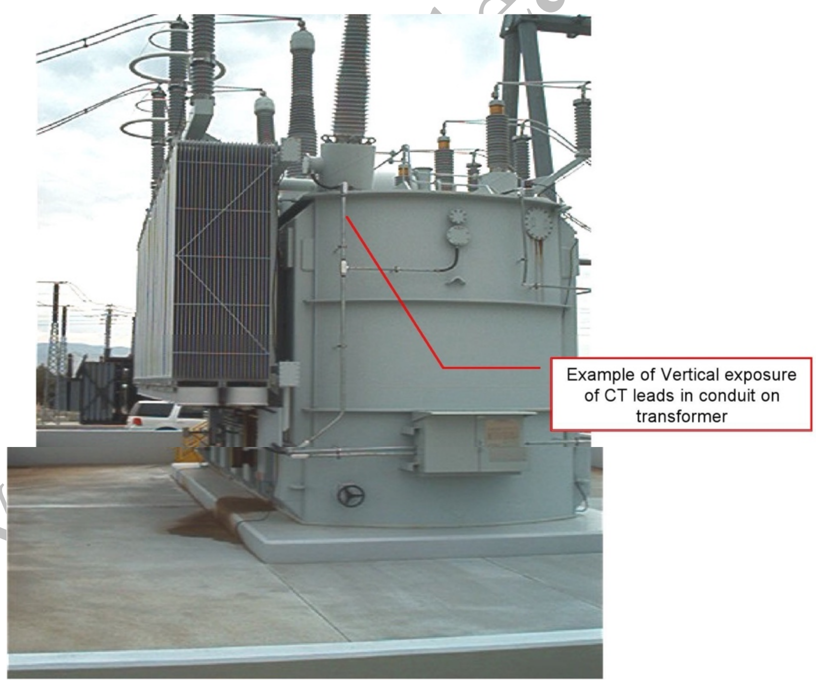


Figure 7-18. Exposure of cable conduits on transformers, p. 7-21

The biggest E1 HEMP concern within a high voltage substation is not the high voltage transmission lines and transformers, but rather the low voltage sensor and control lines that extend from the transformer yard to the relays and other control electronics in the control building.

In Figures 7-19 and 7-20 the sensor and control cables are seen to run slightly below ground in trenways that are "buried" in the gravel in the transformer yard. The length of these cables and the poor electromagnetic shielding of the trenway and the gravel at high frequencies will allow the penetration and coupling of high frequency fields to the cables and the subsequent propagation of these currents and voltages to the control building.

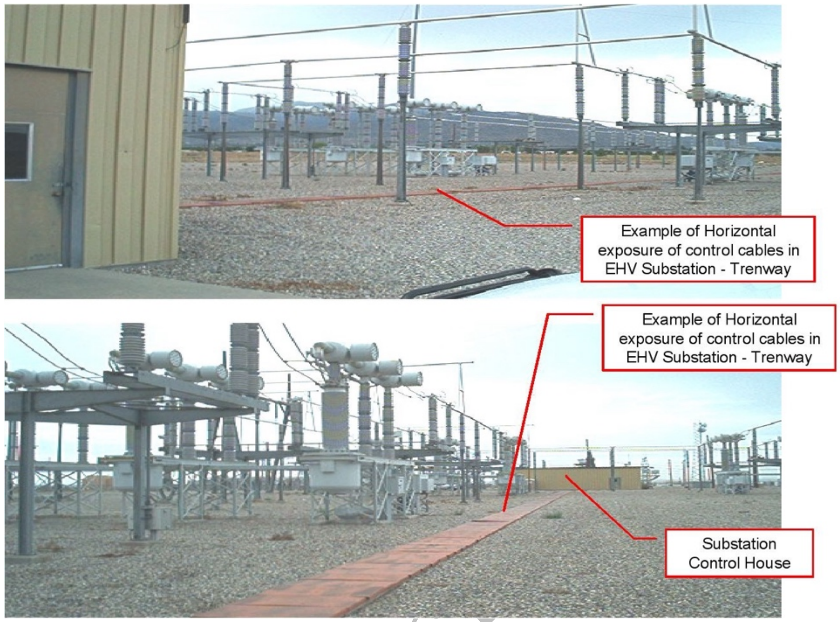


Figure 7-19. Long runs of "buried" cables in low conductivity gravel, p. 7-22

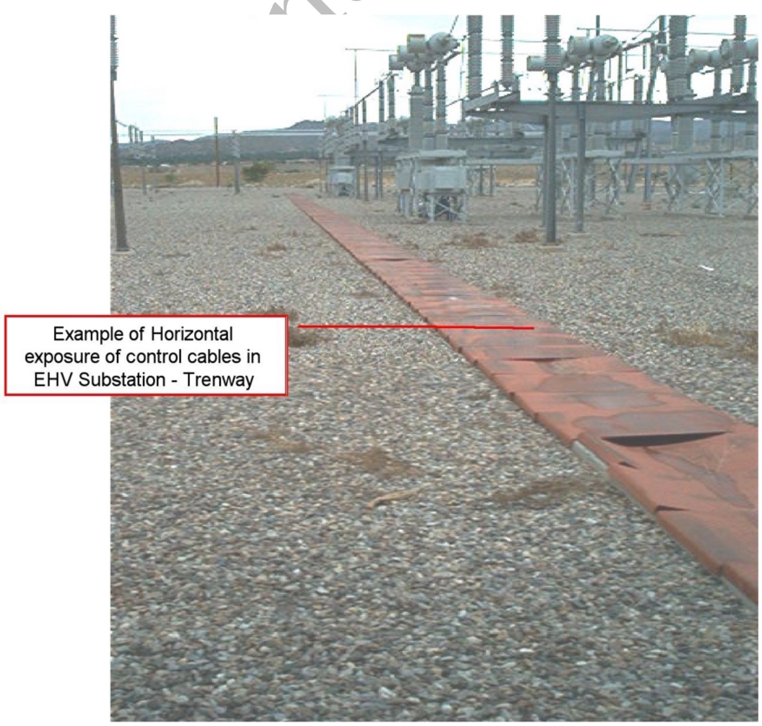


Figure 7-20. Second view of cable trenway, p. 22

In Figure 7-23 cables extend from the j-boxes to the individual racks of equipment. These cables will carry any remaining high-frequency transients that were coupled to the cables outside, and they will also be coupled to by the electromagnetic fields that propagate through the walls of the building.

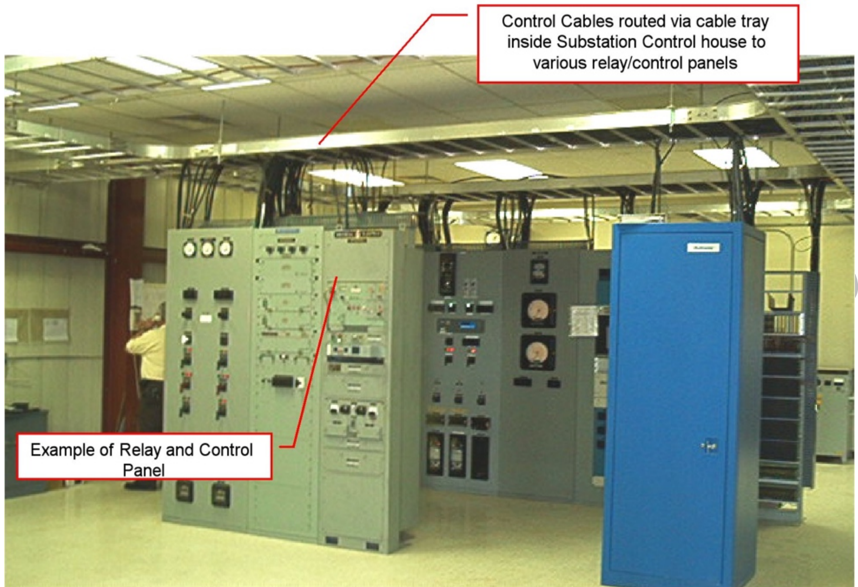


Figure 7-23. Distribution of control cables within building to cabinets, p. 7-18

Insulators on Distribution Powerlines

"Approximately 78% of all electric power delivery to end-users is delivered via 15 kV class distribution lines, as highlighted in Table 7-9. . . the likelihood for an optimum exposure of a segment of the line is high, and that at some point along the feeder the maximum E1 HEMP voltage will be induced, creating a possible insulator flashover." p. 7-25

Table 7-9. Summary of the distribution systems for the U.S. power grid, p. 7-26

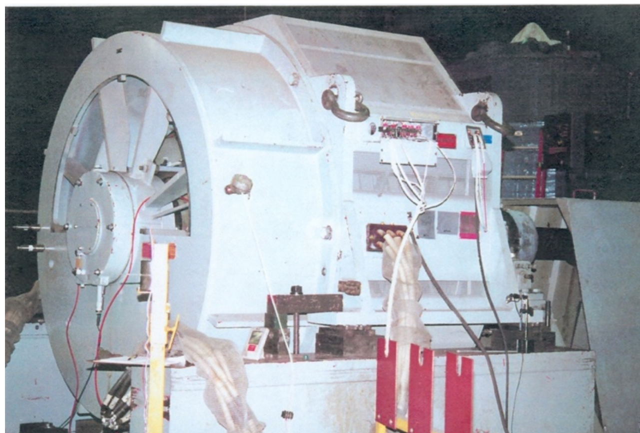
- Distribution systems in the U.S. o 5,15,25and35kV
  - 15kVis77.5%ofallload
  - 35,000 to 40,000 distribution substations
  - Substation size varies from ~1 - 100 MVA with an average of 20 MVA
- Multiple feeders leave the substations
  - 4 to 14 feeders per substation
  - Typically 300 line segments per feeder
  - 60 fault protection and isolation devices per feeder o Average 3 phase feeder length is 10.8 miles
  - 93% of all U.S. feeders are of overhead construction

- End users supplied by feeders
  - 13.0% industrial load
  - 18.4% supply urban/commercial load
  - 11.9% rural load
  - 55.7% suburban load

“Prior analysis of the E1 threat by Metatech indicated that induced overvoltages ranging from 200 kV to over 400 kV (depending on the scenario) can occur on these distribution lines over geographically widespread regions, and that if large scale distribution line insulator failure or flashover occurs, the impacted regions will likely experience power grid collapse.” p. 7-27

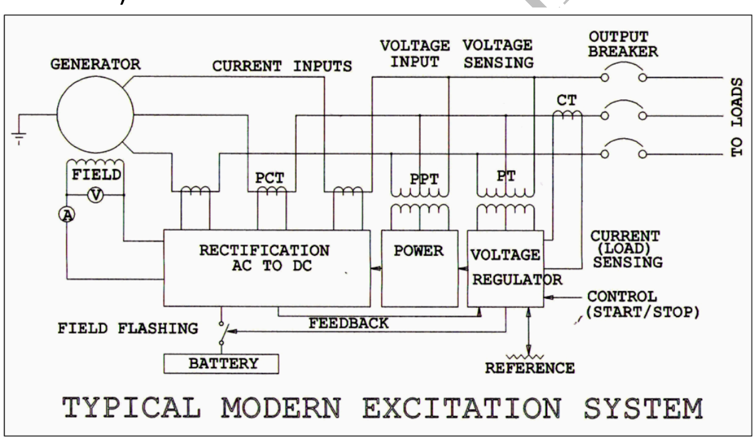
Appendix 2: Emergency Diesel Generator and Battery Bank Schematics

Emergency Diesel Generators



Emergency Diesel Generator at U.S. Nuclear Power Plant:
Nuclear Regulatory Commission. (January 2011). "Chapter 09, *Emergency Diesel Generator.* The *Generator, Exciter, and Voltage Regulation. Rev 1/11," p. 9-21.* https://www.nrc.gov/docs/ML1122/ML11229A143.pdf

EDGs produce power in a range between 1.5 million watts and 8 million watts (1500 kWe and 8000 kWe).[305]



EDG Exciter system (Excitation systems can be defined as the system that provides field current to the rotor winding of a generator.)

Nuclear Regulatory Commission. (January 2011). "Chapter 9, Emergency Diesel Generator, The Generator, Exciter, and Voltage Regulation, Rev 1/11 9-21 of 34 USNRC HRTD, p. 9-30 of 34. https://www.nrc.gov/docs/ML1122/ML11229A143.pdf

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305 MTU Onsite Energy, A Rolls-Royce Power Brand System. (2023). "Emergency Diesel Generators for Nuclear Power Plants", p. 4.https://aa-powersystems.com/wp-content/uploads/3061871_OE_Brochure_NPP_2_14_lay_ES.pdf

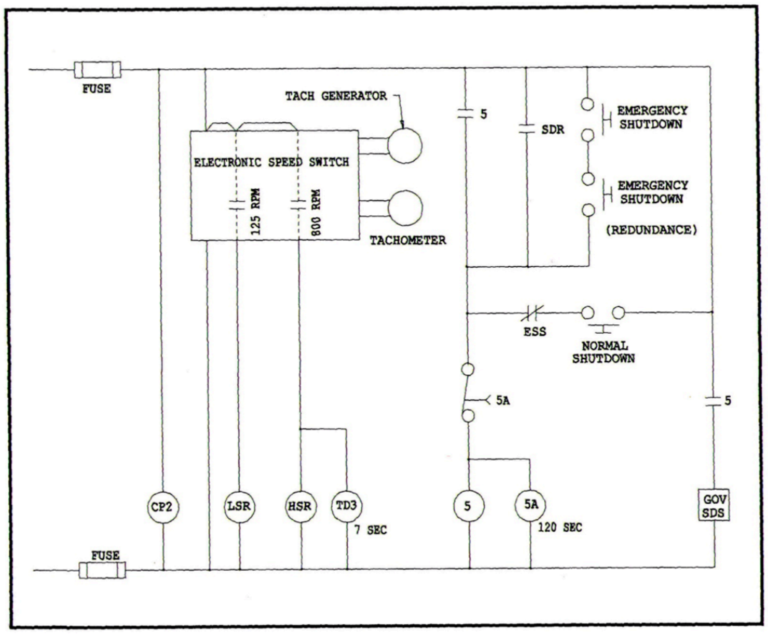


Figure 10-2 Speed Monitoring and Stop Circuitry

Nuclear Regulatory Commission. (January 2011). “Chapter 10, Emergency Diesel Generator EDG Control and Monitoring, Rev 1/11, USNRC HRTD, p. 10-15 of 10-18
https://www.nrc.gov/docs/ML1122/ML11229A158.pdf

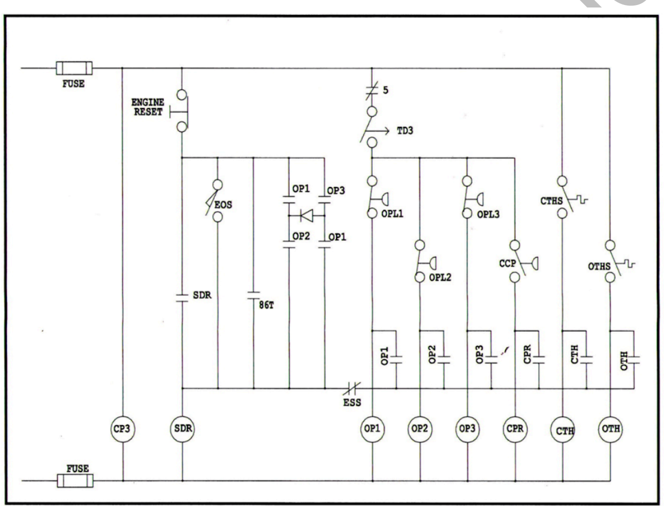


Figure 10-3 Fault Shutdown and Monitoring Circuits

Nuclear Regulatory Commission. (January 2011). “Chapter 10, Emergency Diesel Generator EDG Control and Monitoring, Rev 1/11, USNRC HRTD, p. 10-16 of 18.
https://www.nrc.gov/docs/ML1122/ML11229A158.pdf

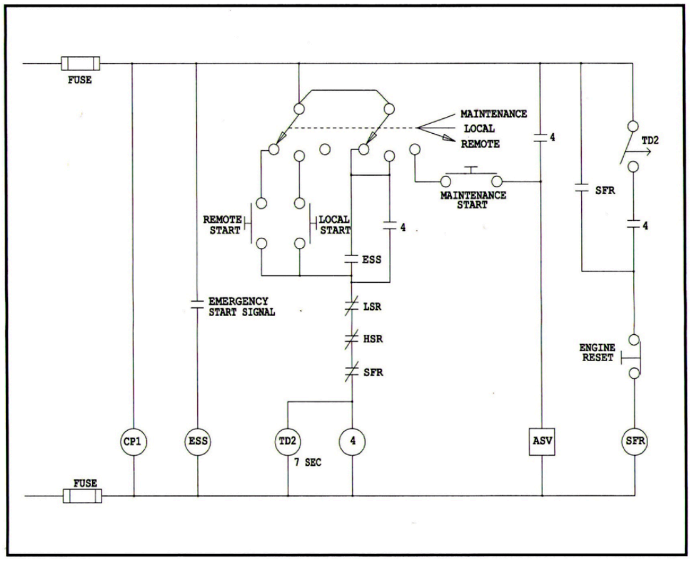


Figure 10-1, EDG starting circuit schematic,
Nuclear Regulatory Commission. (January 2011). "Chapter 10, Emergency Diesel Generator EDG Control and Monitoring, Rev 1/11, USNRC HRTD, p. 10-14 of 10-18
https://www.nrc.gov/docs/ML1122/ML11229A158.pdf

Battery Banks

Solid-state components such as rectifiers, inverters, and high-speed switches are susceptible to damage from HEMP E1

Figures 1 and 3 from Clarke, M. (June 2020). "Battery Backups for Nuclear Power Plants", M.E.T.T.S. Ltd, http://www.metts.com.au/battery-backups-for-nuclear-power-plants.html

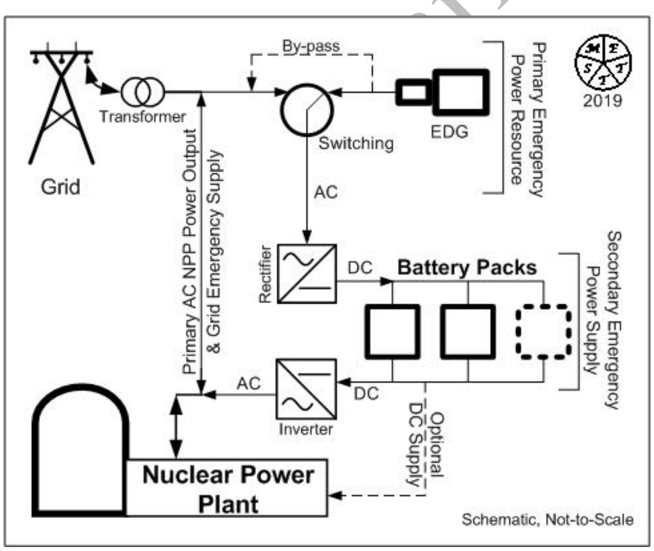


Figure 1. A setup for a battery/EDG power backup system. The batteries can be charged and kept charged either from the grid (usual practice) or from the EDG (during plant testing or emergency grid outages).

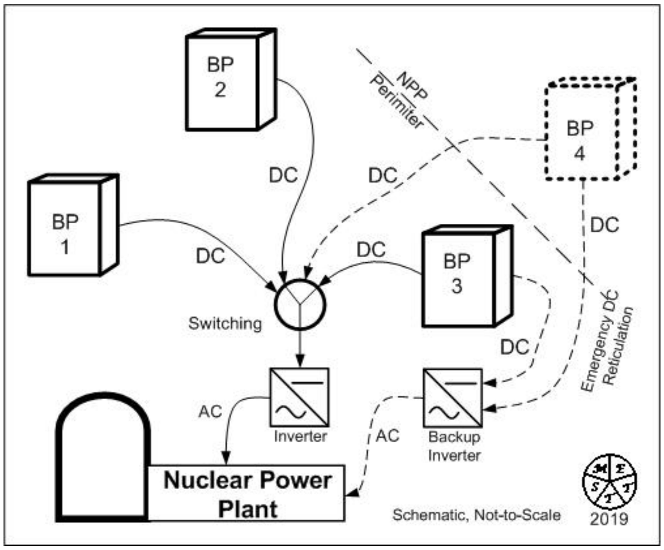


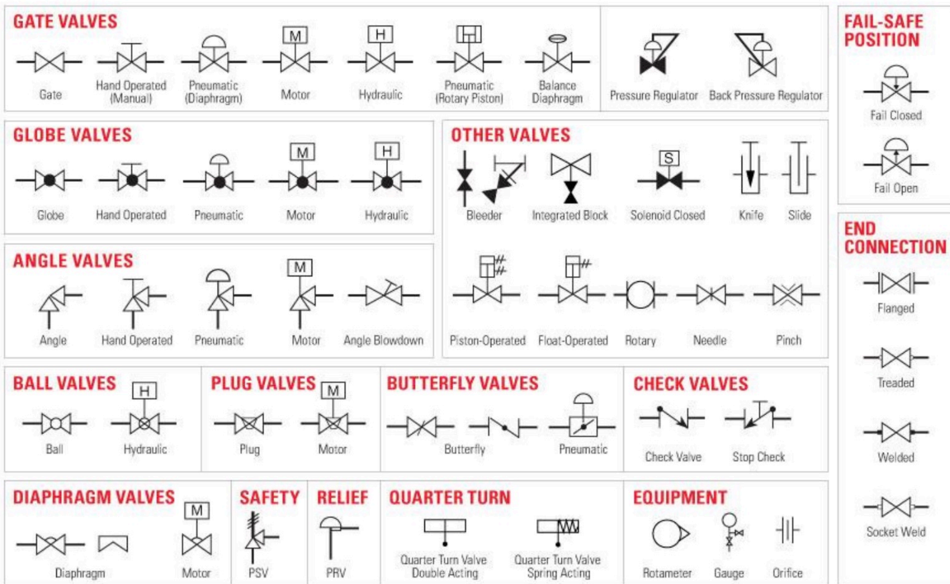
Fig. 3 DC reticulation for a battery storage for a NPP.

The power generated and dispatched by NPPs is high voltage AC; batteries are DC plant. **The two types of plants require power conversion technologies to operate** as part of a generation plant where batteries are used as a backup. **Modern technology for converting DC <--> AC is large-scale electronic solid-state**

Appendix 3: Emergency Core Cooling System Diagrams

Includes location of motor-operated pumps and motor-operated valves

Keys



Kimray Inc. (2023). “The Most Common Control Valve Symbols on a P&ID”. https://kimray.com/training/most-common-control-valve-symbols-pid

Chemical Tweak. (November 4, 2022). “What is P&ID Uses – P&ID Diagram basics symbols, Pumps and Compresses”. https://chemicaltweak.com/p-and-id-diagram-basics/

Boiling Water Reactor (BWR) Diagrams

Source:
Nuclear Regulatory Commission, Reactor Training Branch. (July 2007). "Introduction to Reactor Technology – BWR, Part II, Chapter 10.0, Emergency Core Cooling Systems, pp. 10-10 through 10-13.
https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML12159A165

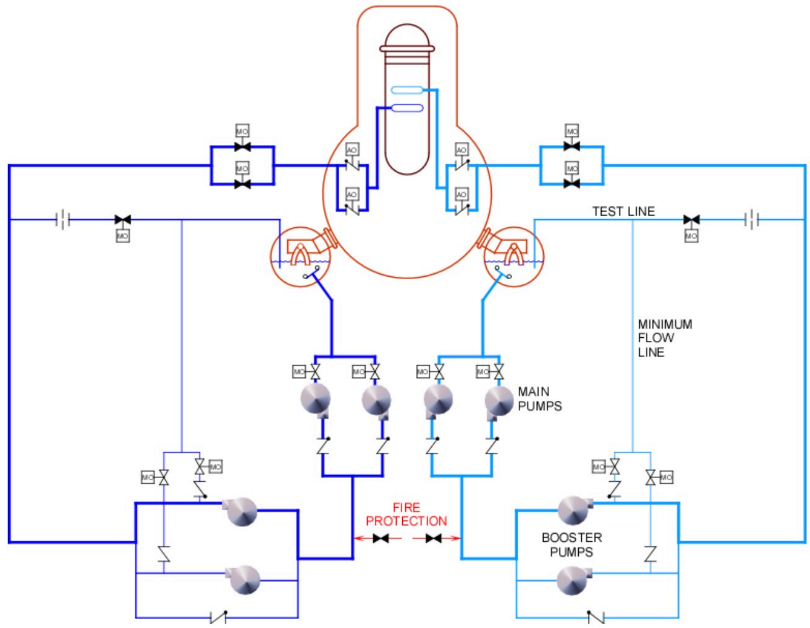


Figure 10.0-1, Core Spray System

Rev 0707 10-10 USNRC HRTD

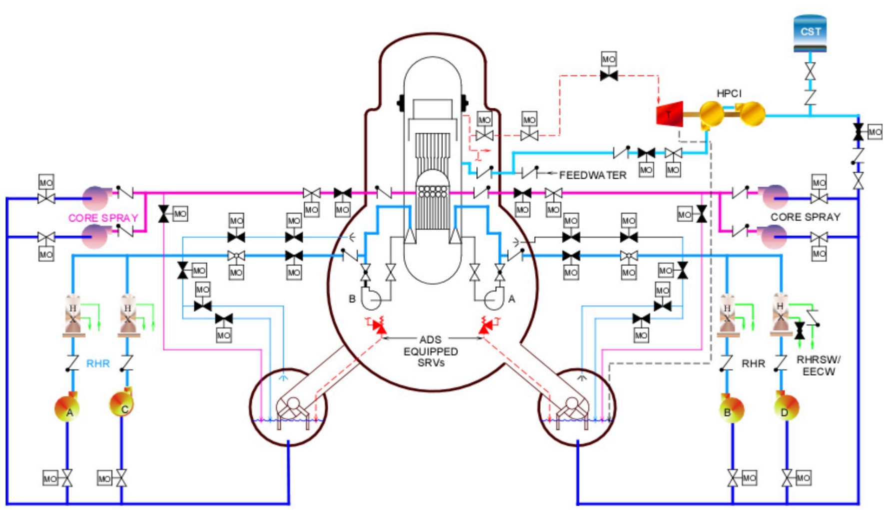


Figure 10.0-2, Typical Emergency Core Cooling System (BWR/3 & BWR/4)

Rev 0707 10-11 USNRC HRTD

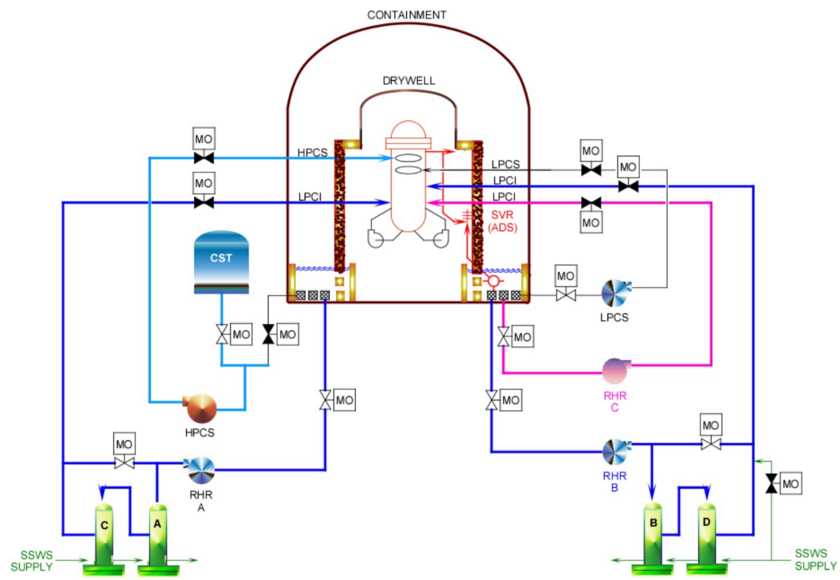


Figure 10.0-3, Typical Emergency Core Cooling System (BWR/5 & BWR/6)

Rev 0707 10-12 USNRC HRTD

Emergency Core Cooling Network

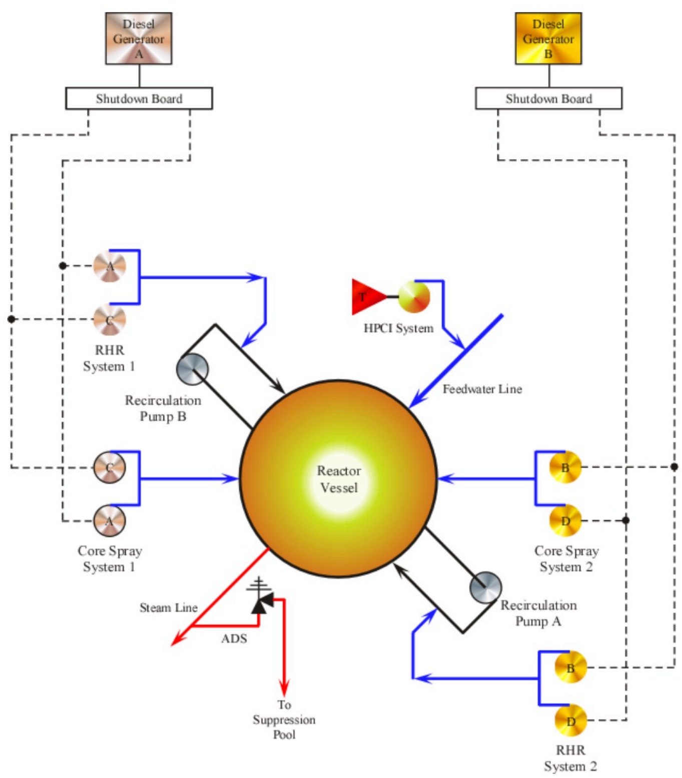
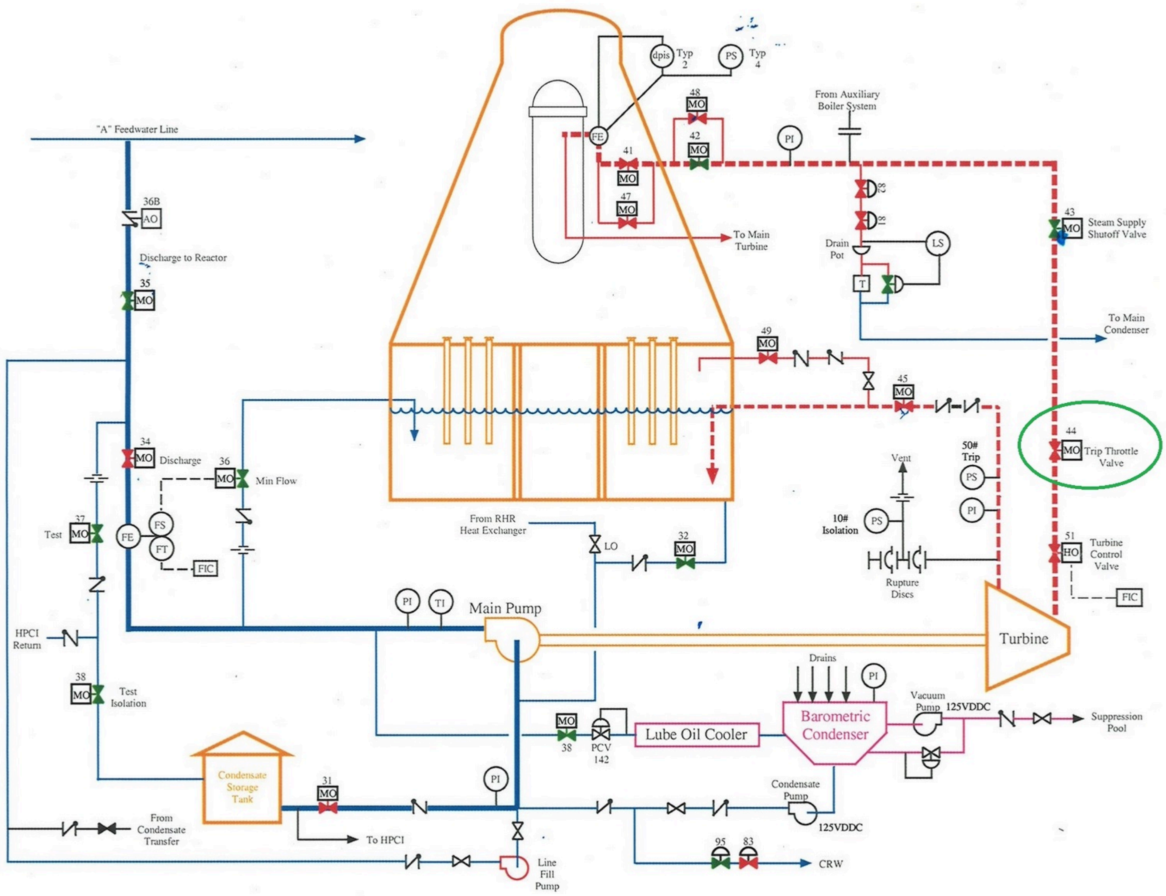


Figure 10.0-4, Emergency Core Cooling Network

Rev 0707 10-13 USNRC HRTD

BWR: Reactor Core Isolation Cooling System

Source:
Lochbaum, D. (August 19, 2014), "RCIC Look See", Union of Concerned Scientists, https://blog.ucsusa.org/dlochbaum/rcic-look-see/



Reactor Core Isolation Cooling System

https://blog.ucsusa.org/wp-content/uploads/2014/07/N36-Figure-1-bwr-ttc-rcic.jpg?_gl=1*auo36d*_ga*MTg1NDE5NDM2NS4xNjczNTQzNDY1*_ga_VB9DKE4V36*MTY3NTYwODI0Ny4xMy4xLjE2NzU2MDgzMDEuMC4wLjA.

Pressurized Water Reactor (PWR) Diagrams

Source to Key and Diagrams:

Nuclear Regulatory Commission, Reactor Technology Training Branch. (April 2008). "Introduction to Reactor Technology – PWR, Part 1, Chapter 1.0 Introduction to Pressurized Water Reactor Systems", Figure 1.0-1, p. 1-14. https://www.nrc.gov/docs/ML1215/ML12159A222.pdf

Key

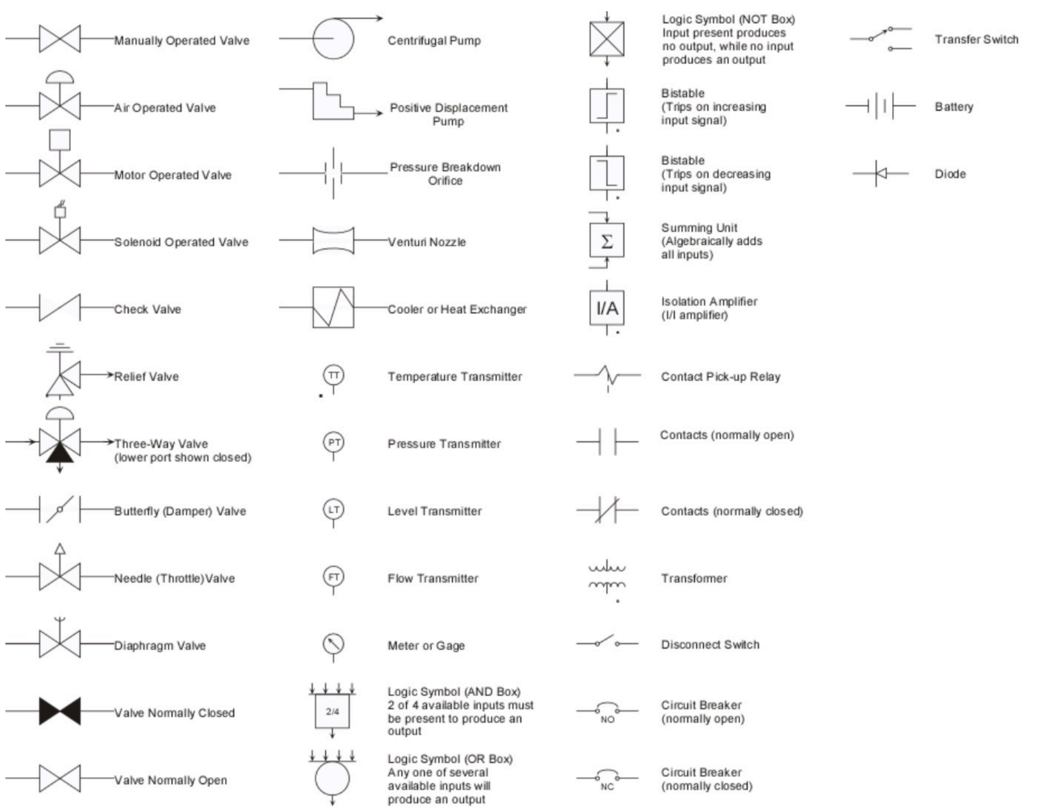


Figure 1.0-1, List of Symbols

Rev 0707 1-13 USNRC HRTD

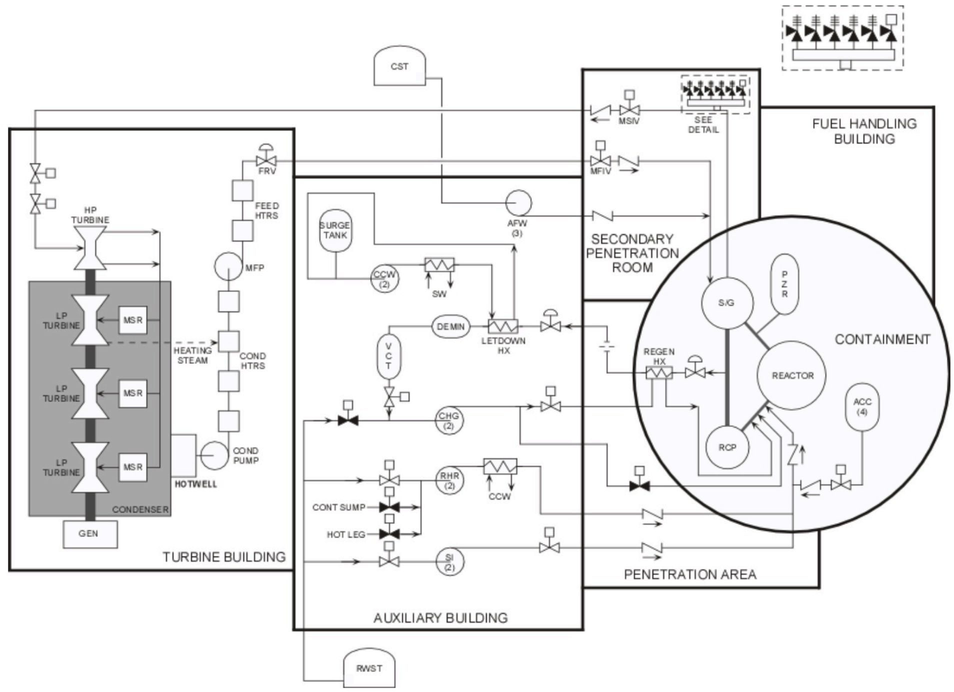


Figure 1.0-2, Plant Systems Composite

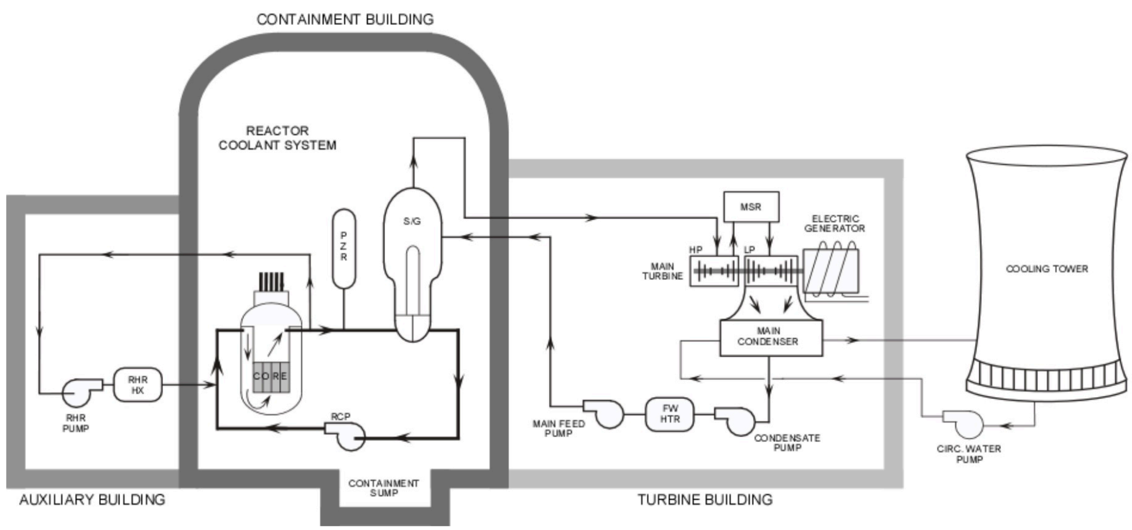
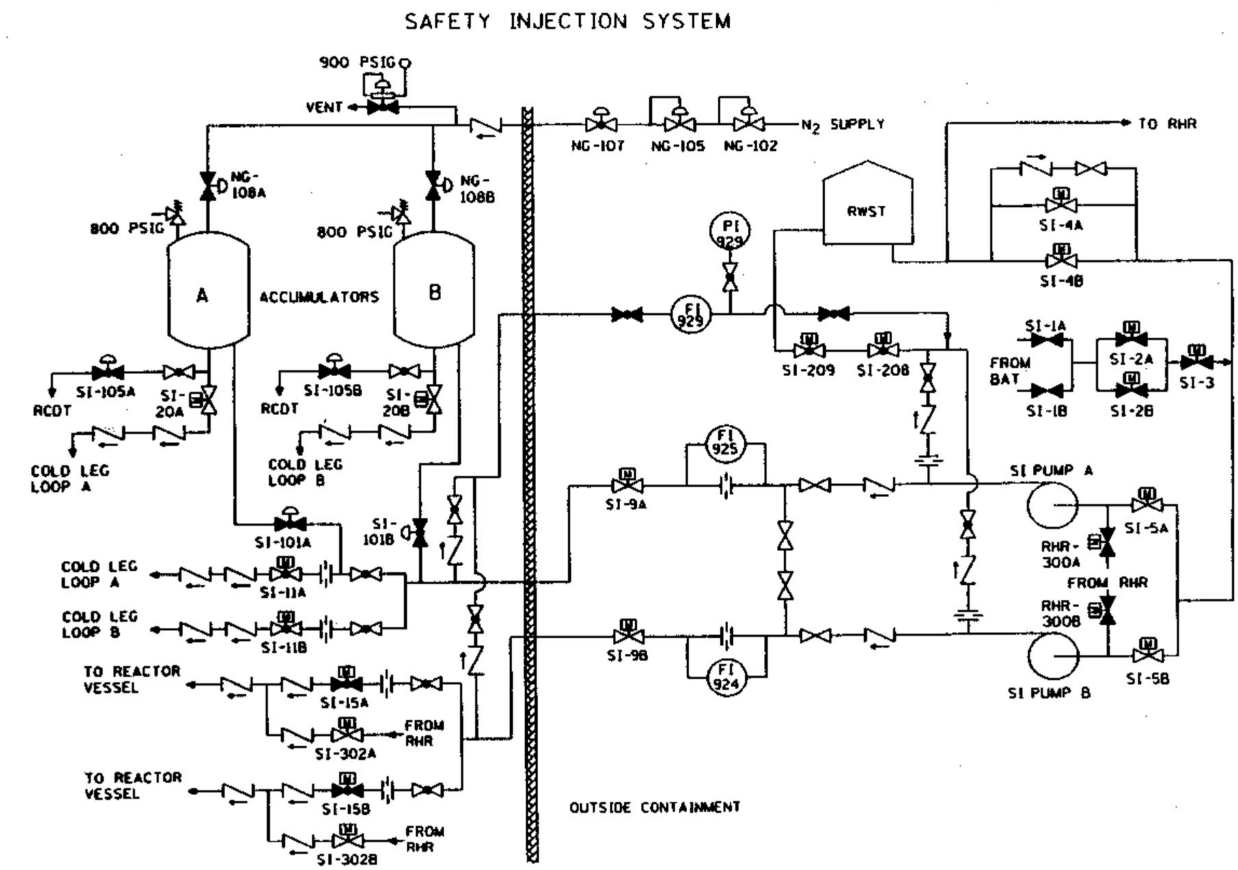
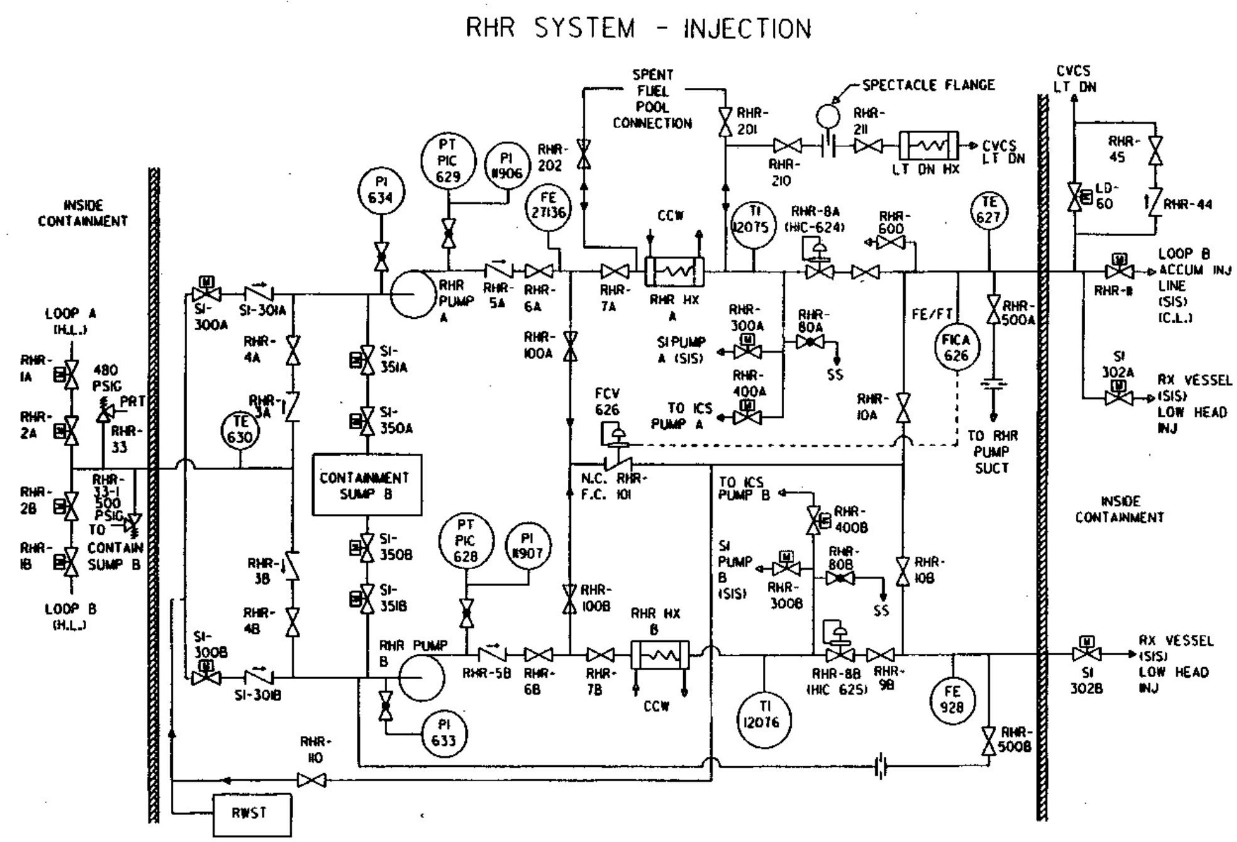


Figure 1.0-4, Basic PWR Arrangement

Source for the next two diagrams:
Nuclear Tourist. (N.D.). "Sample ECCS System Drawings".
http://www.nucleartourist.com/systems/eccs.htm



PWR High Head Safety Injection System



RHR Injection System

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