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Introduction

Chairman Bingaman, Ranking Member Murkowski, and distinguished members of the Senate Committee on Energy and Natural Resources, thank you for the opportunity to testify. I am William Tedeschi, senior scientist and licensed professional engineer at Sandia National Laboratories. Sandia is a multiprogram national security laboratory owned by the United States Government and operated by Sandia Corporation[1] for the National Nuclear Security Administration (NNSA).

Sandia is one of the three NNSA laboratories with responsibility for stockpile stewardship and annual assessment of the nation's nuclear weapons. Within the U.S. nuclear weapons complex, Sandia is uniquely responsible for the systems engineering and integration of the nuclear weapons in the stockpile and for the design, development, and qualification of nonnuclear components of nuclear weapons. While nuclear weapons remain Sandia's core mission, the science, technology, and engineering capabilities required to support this mission position us to support other aspects of national security as well. Indeed, there is natural, increasingly significant synergy between our core mission and our broader national security work. This broader role involves research and development in nonproliferation, counterproliferation, counterterrorism, energy security, defense, and homeland security.

My statement today will focus on the risk of nuclear electromagnetic-pulse (EMP) threats against the U.S. power grid and the potential need to harden the grid against such threats. I have been employed at Sandia National Laboratories for 26 years, where I have done engineering work on the U.S. nuclear stockpile and have assessed a broad range of foreign threats to U.S. national security assets and infrastructures. I am a subject matter expert in nuclear weapon systems and effects, including EMP threats, and in assessing the risks posed by such threats. Part of this expertise came from Sandia having technically supported the congressionally mandated EMP Commission from 2002 to 2008 through targeted EMP testing of a whole range of electronic equipment, assessments of water- and financial-system infrastructure susceptibility, and targeted writing assignments. I was the program manager for that work. My testimony starts with a description of a recent technical peer review of seven reports focused on the topic of this testimony, a peer review that a Sandia team of experts provided to the Federal Energy Regulatory Commission; thereafter, the testimony puts forward the view of the Sandia team on the risk of EMP attacks and the potential need to harden the U.S. power grid against them.

[1] Sandia Corporation is a subsidiary of the Lockheed Martin Corporation under Department of Energy prime contract no. DE-AC04-94AL85000.

Major Points of This Testimony

It is the belief of a Sandia team of experts that

1. Nuclear high-altitude electromagnetic-pulse (HEMP) attacks against the U.S. power grid are of remote likelihood.
2. The susceptibility of the power grid to EMP attacks is not well characterized and should be further addressed with computer-based simulations and experimental testing in order to understand all the risk elements, quantify and reduce uncertainties, and thus fully inform decisions that may be made about the U.S. power grid.
3. Possible approaches to mitigating electromagnetic threats to the U.S. power grid could be graded hardening, whereby selective hardening would be accomplished easily and cost-effectively while addressing new and emerging threats to the grid, or selective hardening for protection of some critically important U.S. nodes.

Electromagnetic Pulse (EMP) Threats to the U.S. Power Grid

Sandia Team Provided a Technical Peer Review for the Federal Energy Regulatory Commission

The Federal Energy Regulatory Commission (FERC) recently requested Sandia to do a peer review of seven reports (more than 700 pages in length) on electromagnetic threats to the U.S. power grid and on possible actions for mitigating such threats. A team of six subject matter experts (including myself) in EMP threats and effects, including damage susceptibility and consequences, conducted this work. Included in the team were two members with significant expertise in modeling national infrastructures and their interdependencies. Our assessment and recommendations do not constitute a position of or an endorsement by Sandia National Laboratories. Rather, they represent the conclusions the team reached after conducting a technical service Sandia is frequently called upon to perform for national security purposes. The team's high-level observations and findings were threefold:

- The reports are comprehensive, and the authors' knowledge about the U.S. power grid design and operations, as well as solar-induced and nuclear high-altitude EMP (HEMP) environments, is impressive.
- The work represents an excellent start on modeling a very complex problem, but it is not yet complete and, in our view, should not be the basis for any short-term national decisions on whether and to what extent to harden the U.S. power grid **solely** against nuclear HEMP threats.
- Further study of this complex problem is recommended in order to include computer-based simulations and experimental testing to better understand, validate, and add to the existing work so that a complete understanding of all the risk factors and associated uncertainties can be obtained to support ongoing decisions.

Some additional general comments about the reports that the Sandia technical peer review team provided to FERC include the following:

The identified threats appear to be worst-case nuclear HEMP threats, but no details are provided to indicate the seriousness and plausibility of such threats or what might be the full spectrum of possible HEMP threats. Not all nuclear bombs are created equal; technical details matter—details not only on the potential severity of nuclear HEMP effects, but also

on the likelihood of such threats ever materializing. Further elaboration on this aspect is warranted but must be done in a classified setting.

Numerous assumptions are made about the nuclear HEMP environments' coupling efficiency into the exposed power grid and about the susceptibility of key system elements and the upset or damage that might occur to those key elements (that is, protective features, control systems, and the high-voltage transformers). Few to no data and only a few referenced citations and limited technical analysis are offered to buttress the assertions made. Many assumptions are also made about the power grid and the type and implementation of its equipment. The power grid referenced in the reports as the "normal grid design" is portrayed without any information about validation from utilities. Assumptions about age, design, and failure thresholds of transformers introduce additional uncertainty and are based on limited samplings of transformers of a particular type and from a clear source. All the assumptions point to large uncertainties in the output results and interpretations from the model; therefore, statements on the number of "at-risk" transformers and the severity of the regional damage should be viewed as illustrative only. More modeling and simulation and experiments to characterize the response space of these key elements are recommended.

Finally, in our team's view, the reports' assessment of possible effects on the U.S. power grid as a result of nuclear HEMP attacks is too negative, based on a series of compounded, apparently worst-case assumptions. The reports lack discussion of the effect of possible uncertainties and mitigators on the results.

More detailed and specific technical comments were submitted to FERC for its consideration, and those can be provided upon request.

Sandia Team's Position on Electromagnetic Pulse (EMP) Threats to the U.S. Power Grid

Background on Nuclear High-Altitude EMP (HEMP) Threats: Effects, Damage, and Hardening

Nuclear EMP effects at Earth's surface are created by nuclear bomb explosions high inside the atmosphere (at an altitude of 40–100 kilometers) and in near outer space (from 100 kilometers to hundreds of kilometers above Earth's surface). According to publicly available information, both the United States and Russia experienced and characterized this class of nuclear weapon effects in the early 1960s during their high-altitude nuclear tests. The type and yield of the bomb and the altitude at which it is detonated primarily determine the strength of the EMP effects at ground level. Once the nuclear bomb's parameters are defined, predicting nuclear HEMP environments with computer-based models is a well-established capability in the United States.

The hostile nuclear EMP environment is created by the gamma-ray output (as well as x-rays and bomb debris for exo-atmospheric bursts) from the nuclear explosion (the "source") and the subsequent electron generation and dynamics within the atmosphere and magnetic field perturbations outside the atmosphere. Nuclear bomb explosions at high altitude in the atmosphere and in near-Earth space create three distinct components of EMP threats that are characterized by the timeframe over which they occur after the burst (from nanoseconds to a microsecond, from microseconds to a second, and from a second to many minutes). These electromagnetic threats are termed the E1, E2, and E3 components of nuclear HEMP. Each EMP threat component has

different electric field strengths (typically ranging from kilovolts per meter for E1 to volts per kilometer for E3) and frequency content (ranging from many hundreds of megahertz to many hertz) that ultimately determine how much current is "coupled" into which parts of the exposed power-grid infrastructure elements, and whether or not that component will be temporarily or permanently disabled.

The EMP waves travel downward (or "propagate") to the ground at the speed of light, exposing objects to the EMP threat waveforms. The amount of damage, if any, to the exposed electronics (for example, grid control centers and supervisory control and data acquisition, or SCADA, elements) and objects (such as transformers) connected to long electrical conductors (such as long power and copper communication lines) depends on how much energy in the form of induced electric current couples into the object or item that was exposed to the EMP. The added current going into an exposed electronic component or item of electrical equipment represents an "insult," over and above the normal operating conditions within the component that can then cause an upset or burnout of the object. The U.S. nuclear EMP effects community has the computational ability to model the created EMP threat waveforms from the source and propagate them down to the ground and thereby to exposed objects. This community is also generally able to calculate how much current is induced in exposed conductors (for example, long lines) and well-defined discrete objects (such as buildings and electronics boxes). However, the more complicated the exposed object's design and geometry (for example, the design and geometry of a transformer), the more difficult it is to computationally model the induced current. Therefore, experiments are also conducted to help characterize the induced, or coupled, current insults as a complement to computational modeling approaches.

The ultimate response of the exposed component or subsystem depends on the magnitude of the incoming current insult (how many amperes and over what timeframe). Sometimes, the high current insult burns out a sensitive device or circuit inside the exposed object, and the item is then permanently damaged. That is, the component will no longer work, and it would need to be replaced with a new component before system functionality and operability could be restored. For more moderate incoming current insults, local heating is generated inside the object because of current dissipation, and the local heating can have a temporary disruptive effect. Once the generated heat inside the object is dissipated, the object can return to normal functionality, but sometimes this return to functionality occurs only after human intervention to power down and power up the object. If the incoming current insult is low and not significant, the object can absorb the current insult and continue operating as designed. If the component is simple (for example, an electrical circuit or device), we can model the response of the exposed object to the current insult and thus determine whether it would be upset or damaged. However, many electrical components, subsystems, and even integrated systems have complex designs and constructions, and therefore we must resort to a combination of computer-based models and experimental test-based approaches to understand their response to the EMP-caused current insults. For complex, interdependent linked systems, such as the U.S. power grid, it is essential that computational and experimental modeling approaches be combined in order to verify and validate that the correct problem is being modeled and acquire the right level of confidence in the results.

Once an electronics-based device, component, subsystem, or system has been fully characterized to nuclear HEMP threats and has been found to be susceptible or vulnerable to the EMP-induced current insult, adverse effects (such as temporary or permanent failure) can be mitigated in several ways. One would want to consider mitigating the adverse affects, especially if that component is a critical element in a larger networked system. A common approach for mitigation is to harden the

exposed object(s) against the EMP threat using a range of well-established design hardening techniques, such as faraday-cage shielding, grounding, filters, fast-acting current shunt devices, and responsive control systems to manage the effects that could start to cascade across a larger network of linked objects. If hardening against EMP effects is done early in the design definition and development process, before manufacturing, it can be added in the easiest and most cost-effective manner. The designer must know ahead of time the expected nuclear HEMP threat environments and the required level of hardness for the exposed component or subsystem needed for continued operation after the EMP attack.

The U.S. electric power grid contains some level of inherent hardness to the three nuclear EMP components. E1 (the high-frequency component) corresponds to electromagnetic interference threats from nearby transmitters (for example, cell-phone, radar, TV, and Wi-Fi transmissions), and electromagnetic compatibility standards are followed to protect against such electromagnetic threats. The E2 (mid-frequency) component corresponds to the EMP from nearby lightning strikes, which the power grid is already protected against. Finally, E3 (the low-frequency component) corresponds to solar-induced geomagnetic storms and the resultant ground-induced current threats, which the power grid is already resilient against to a degree and is more resilient against in some northern latitudes.

A key unanswered question remains: How much more severe would the full range of possible nuclear-driven E1, E2, and E3 components be, and what level of protection would the existing power grid have against HEMP effects generated by a nuclear detonation? The answer depends, in part, on the type, yield, and detonation altitude of the nuclear bomb that produces the HEMP effects, the real-world orientations of power grid elements relative to the detonation, any inherent shielding properties of the exposed infrastructure elements, and the robustness of the exposed elements to withstand the EMP insult. More computer-based modeling and simulation, as well as experimental testing, would provide a basis for a more complete understanding of the response of the power grid to a HEMP attack and of the specific hardening measures to be considered for addition to the grid.

As new technologies are studied, developed, and added to the power grid (such as smart grid monitoring and control), being aware of and considering the evolving threat space (for example, intentional electromagnetic interference) and natural environments (such as variations in solar geomagnetic storm intensity) that could affect the performance and reliability of the new technologies may offer opportunities to add some level of inherent hardness against specific nuclear HEMP environments.

Assessing the Risks Posed by Nuclear High-Altitude EMP (HEMP) Attacks

In assessing the risk posed by nuclear HEMP attacks, we use the classical risk equation, where risk is expressed in terms of likelihood (or probability) of the attack, susceptibility (or vulnerability) to the hostile environments created by the attack, and consequence (or system-level impact) as a result of the attack.

In Sandia team's view, the likelihood of a nuclear HEMP attack occurring above the United States is very remote. The advanced nuclear weapon states have had the capability to do significant damage against the United States and our power grid for many decades, but they have been and hopefully will continue to be deterred from such attacks by a strong U.S. strategic deterrent. Some argue that terrorists who might someday gain possession of a nuclear device can conduct a similar type of attack and generate the same amount of damage. According to the team, the assertion that terrorists can use a nuclear warhead in a crippling HEMP attack against the United States is not

credible, and the likelihood of something like that happening is low. More detailed explanation can be provided in a classified venue.

In terms of actual susceptibility of the power grid to nuclear HEMP effects, the limited available data on damage effects make it difficult to know what will precisely happen to exposed elements across the grid, especially to the large high-voltage transformers. Given the amount of investment associated with potentially hardening against EMP effects, additional computational analysis and testing are needed for higher confidence in whether and to what extent exposed elements are susceptible to any temporary or permanent EMP damage effects. While computer modeling work to date has been extensive on the induced currents on exposed power lines, very few experimental data exist on how the exposed grid elements (the controllers, protective devices, high-voltage transformers, etc.) would actually respond to higher than normal currents. Highly instrumented testing of key power-grid components to E1 and E3 threat insults is recommended and should include characterizing how failures (physical damage) occur and at which insult levels they occur. Such data would help validate existing power-grid models, reduce inherent uncertainties about the amount of damage induced, and provide more confidence in the results.

Finally, not enough data exist to confidently assess the extent of any power-grid outages from a nuclear HEMP attack and the amount of time needed for recovery. Several real-world examples have been studied of how the grid might respond to E3-like effects (for example, the March 1989 Hydro-Quebec grid collapse due to a severe solar geomagnetic storm and the August 2003 power outage in the Northeastern United States), and table-top exercises have been developed on how utilities would find and fix the resultant EMP-induced damage and bring the grid back online after a certain period. However, one can only parametrically evaluate the impact of nuclear E1 and E3 attacks because we do not know the level and extent of damage that would actually occur. If additional data were to become available on E1 and E3 damage effects and lethality levels of critical power-grid components, then the basis would exist for more-confident U.S. power grid simulations of the extent and magnitude of damage and the resultant recovery times.

Summary and Conclusions

From an integrated "total" risk perspective, the Sandia team considers nuclear HEMP threats to be of remote likelihood. Also, the true extent of the grid's susceptibility and vulnerability to such effects (be they temporary, permanent, or even not present) and the resulting consequences (damage extent and period they would be lasting) are mostly unknown, except for the assumed worst-case environments and assumptions made in the current nuclear HEMP threat studies that the Sandia technical peer review team evaluated. We commend FERC and the authors of the studies for their excellent work to date on evaluating the impact of EMP threats to the U.S. power grid. However, we respectfully suggest that more computational and experimental work is required before fully informed decisions can be made about where and to what extent the power grid should be hardened **solely** against nuclear HEMP threats. If the decision is made to protect the power grid against a broader set of likely EMP threats, including solar geomagnetic and electromagnetic interference threats, then an awareness of nuclear HEMP environments and effects should also be considered.

The Sandia technical review team recommends that this complex problem be studied in more depth in order to include results from additional computer-based simulations and experimental testing. Specifically, under nuclear HEMP threat conditions, how do high-voltage transformers and their protection and control elements respond to the range of induced current insults, and if they fail, how do they fail? Answering such questions would provide critical data to enable better

understanding and validation of results by advancing a complete understanding of all the risk elements, as well as quantification and reduction of uncertainties in order to fully inform decisions that may be made about the U.S. power grid. We suggest that a graded hardening approach could be considered, whereby selective hardening could be accomplished easily and cost-effectively, in combination with addressing new and emerging threats to the grid (for example, intentional electromagnetic interference). Also, by further evaluating the consequence of EMP attacks on mission-critical U.S. installations and functions (for example, important U.S. war fighting or continuity of operations), specific sites may be identified that may require selective EMP hardening.