Joyce L. Connery, Chair
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DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Washington, DC 20004-2901

June 3, 2024

The Honorable Jennifer Granholm
Secretary of Energy
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-1000

Dear Secretary Granholm:

The Defense Nuclear Facilities Safety Board (Board) has completed its review of maintenance practices for aboveground and underground electrical cable systems in the Department of Energy (DOE) defense nuclear complex. The review included programs that mitigate in-service failure of both safety and non-safety related electrical cables and examined how uniformly DOE's defense nuclear facilities implement the applicable DOE directives and industry consensus standards and guidelines. Electrical cabling plays a crucial role in ensuring nuclear safety; therefore, it is essential to develop robust maintenance practices to maintain cable integrity. Given the age of the defense nuclear complex and its supporting electrical infrastructure, a significant portion of the complex's electrical cabling is near or past its typical 40-year design life. Accordingly, robust maintenance practices and effective repair and replacement programs have become increasingly essential to ensure continued system safety and reliability.

The Board's staff team identified numerous good practices for electrical cable maintenance; however, DOE could significantly improve the safety and reliability of its electrical systems by ensuring that a standard plan for cable maintenance is applied across the complex. An effective plan would outline a comprehensive and uniform strategy that specifies the procedures, frequency, and techniques for maintaining electrical cables. Such a plan would also cover all aspects of cable care, from routine inspections to detailed condition monitoring, ensuring consistency in maintenance practices. Using such a plan, DOE could deliver greater safety and reliability in electrical power cable operation within the complex, for both its current and future missions.

The Board is providing the enclosed report for your information and use.

Sincerely,

Joyce L. Connery

Enclosure

c: Mr. Joe Olencz, Director, Office of the Departmental Representative to the Board

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Staff Report

April 4, 2024

Maintenance of Electrical Power Cabling in the Defense Nuclear Complex

Summary. The Defense Nuclear Facilities Safety Board's (Board) staff team conducted this review to evaluate and compare how different Department of Energy (DOE) contractors maintain the electrical power cabling supporting defense nuclear facilities. The reliability of site electrical infrastructure is a critical input assumption in many nuclear safety analyses as it supports the operation of multiple safety, defense-in-depth, and non-safety systems. The review focused on: (1) maintenance of aboveground and underground electrical cabling and (2) programs that mitigate in-service failures of power cables.

Numerous governmental regulations and industry consensus standards assess the integrity of electrical cabling and its insulation systems; however, these are largely focused on establishing coverage and reliability requirements for electric utilities and do not specify the particular maintenance and testing programs that must be implemented to achieve that reliability. As a result, neither the electrical power industry nor DOE uniformly implement programs consistent with the myriad of guidance and requirements. Ultimately, the appropriate maintenance methodology varies based on cable function, installation, and the type of insulation system used.

While DOE directives (e.g., DOE Order 420.1C, *Facility Safety*) offer some direction for safety-related cabling, DOE documents contain minimal guidance for the maintenance of general electrical infrastructure. Consequently, the staff team compared cable maintenance practices across four DOE facilities to help identify the existing baseline (minimal common subset of maintenance being performed) and document best practices currently in use. The staff team selected the Hanford Site (Hanford), Los Alamos National Laboratory (LANL), Nevada National Security Site (NNSS), and Savannah River Site (SRS) for this review.

Background. Given the age of the defense nuclear complex and its supporting electrical infrastructure, a significant portion of the complex's electrical cabling is near or past its typical 40-year design life. Accordingly, robust maintenance practices and effective repair and replacement programs have become increasingly essential to ensure continued system safety and reliability.

Why Focus on Electrical Cabling?— Electrical cabling plays a crucial role in ensuring nuclear safety; therefore, it is essential to develop robust maintenance practices to maintain cable integrity. Cable-supplied electricity directly supports certain safety functions (e.g., backup power for credited active ventilation) across the complex. Reliability of safety equipment is a critical design element, and adequate maintenance is essential over the life of the system to protect that element.

Electrical cabling offers a unique maintenance challenge. Because of its scale (i.e., often kilometers in length) and various installation practices, typical maintenance techniques such as visual and infrared inspections can have limited effectiveness. Underground cabling may be better protected from the elements, but it is more difficult to inspect as accessibility is generally limited to cable termination points, which further reduces the available maintenance techniques and ability to repair failures.

What Are the Guiding Maintenance Tenets?—There is no single unifying set of maintenance requirements for electrical power cables. Multiple industry standards (e.g., those promulgated by the National Fire Protection Association [NFPA], Institute of Electrical and Electronics Engineers [IEEE], International Electrotechnical Commission [IEC]) discuss general requirements, such as following manufacturers' recommendations but offer few specifics. However, the basic tenets of maintenance requirements are like those for other distribution equipment: maintain cleanliness, ensure tight connections, inspect for physical damage, and monitor for degradation.

What Is Adequate Maintenance?—There is no single definition for adequate maintenance because every system has a different design, mission, and installation environment. NFPA 70-2023, *National Electric Code* [1] offers one key insight with the definition of adequacy, as it states that both proper installation and maintenance are necessary for safe operation. Therefore, one potential definition for adequate maintenance is the set of activities that keep equipment operating in a safe manner. Currently, safety in the context of NFPA 70 is focused on two aspects: (1) protection of personnel from electrical safety hazards and (2) the quality of installation and maintenance practices that reduce the likelihood of an electrical fire. The staff team focused its review on this second aspect of safety.

Site Interactions. The staff team conducted this assessment primarily through a review of site documents related to the maintenance and inspection of electrical distribution cabling. Throughout 2023 and early 2024, the staff team held teleconferences with Hanford, LANL, NNSS, and SRS to verify its observations and request additional details. The purpose of these discussions was to share the staff team's approach, confirm additional details related to the reviewed documents, and, ultimately, to communicate the collective observations from the staff team.

Staff Observations. Safety bases often assume a reliable normal electrical power supply. Loss of electrical power is frequently an event precursor and can initiate certain accidents. On average, the electrical power grid in the United States is considered highly reliable; however, loss-of-power events are typically considered as "anticipated" in the hazard risk ranking bins in documented safety analyses. While this risk binning may appear conservative, there is a significant difference between nearly 10^{-2} failures[1] per year (associated

[1] DOE-STD-3009-2014, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis*, notes "anticipated" events as those with a probability of greater than 10^{-2} and defines them as events "…that may occur several times during the lifetime of the facility (incidents that commonly occur)."

with a risk binning of “anticipated”) and multiple yearly failures (as witnessed by many normal electrical customers across the United States).

DOE achieves a more reliable electrical supply for its defense nuclear facilities compared to typical electrical customers through the robust design of its sites’ electrical infrastructure. Sites are typically fed from at least two offsite power generating stations connected to the site electrical grid via separate (and redundant) feeders. And once power is onsite, nuclear facilities are typically fed, independently, from multiple site substations or feeder circuits. This redundancy greatly reduces the potential for the loss of electrical power (getting closer to the 10^{-2} failure frequency). However, sites that rely on poorly maintained or unmaintained equipment have an increased likelihood of electrical failures. Operating equipment past its design life reduces a system’s original design margins. Notably, some DOE sites have underground cabling that has exceeded its design life.

The next several sections of this report capture the staff team’s observations on individual aspects of the site maintenance programs and the available guidance. The conclusion of the report summarizes the maintenance practices that are largely common among the sites and augments them with the best practices identified across these four sites. The resulting summary captures a framework for DOE’s consideration in implementing a more universal cable maintenance strategy.

Electrical Maintenance Standards. Industry consensus electrical standards provide some guidance regarding the maintenance of cabling. However, there are few hard requirements specific to cables outside of the general information for all safety-related electrical equipment. Tables 5 and 6 of DOE Order 420.1C identify these relevant codes and standards. The cited NFPA, IEEE, and IEC standards provide some requirements for safety cabling, but very limited guidance for non-safety equipment.

Notably, NFPA recently upgraded NFPA 70B-2023, *Standard for Electrical Equipment Maintenance* [2], from a recommended practice to a consensus standard. The purpose of NFPA 70B-2023 is “to provide for the practical safeguarding of persons, property, and processes from the risks associated with failure, breakdown, or malfunction and a means to establish a condition of maintenance of electrical equipment and systems for safety and reliability.” It is one of the few industry standards that delineates clear requirements for cable maintenance, though it still leaves significant flexibility with how to meet them. Because NFPA 70B was historically only a recommended practice, and not a set of requirements, its implementation is inconsistent across the defense nuclear complex. Title 10 Code of Federal Regulations Part 851 (10 CFR 851), *Worker Safety and Health Program*, does not currently require adherence to NFPA 70B. As a result, implementation of NFPA 70B is inconsistent across the defense nuclear complex. DOE could address this inconsistency by updating 10 CFR 851 to include the revised NFPA standards

Now that NFPA has revised NFPA 70B to a consensus standard, there are a few clear high-level requirements for electric cables. Chapter 18, *Power Cables and Conductors*, Section 18.3, *Periodic Maintenance Procedures*, captures most of these requirements and provides tables listing the different requirements for various cable types and installations. Chapter 18 discusses both cleanliness and visual inspections, but the strongest requirement is 18.3.5, *Electrical*

Testing, which states that "Power cables and conductors shall be electrically tested in accordance with Table 18.3.5." Table 18.3.5 lists the different tests that can be used to fulfill the requirement for low- and medium-voltage cables and their connectors. The requirement provides a few options for medium-voltage cables, but the requirement is clear that insulation resistance testing shall be part of cable maintenance programs going forward.

Best Practices—While multiple sites already cite NFPA 70B (the recommended practice) as an input to their maintenance requirements, Savannah River Nuclear Solutions (SRNS) personnel are in the process of evaluating the new standard. SRNS already has incorporated some NFPA 70B recommended practice guidance into its site procedures. SRNS personnel informed the staff team that they intend to develop an implementation plan for incorporating the requirements of the new NPFA 70B standard into their site procedures. The other sites the Board's staff evaluated did not indicate they were proactively reviewing the new standard.

Potential Improvements—Both DOE and its contractor personnel could strengthen their overall knowledge and approach to cable maintenance by increased participation in industry consensus standard bodies. Participation in these organizations both deepens staff knowledge of industry standards and allows staff to assist in the development of standards to address evolving problems in the industry. For example, the Nuclear Power Engineering Committee under IEEE currently manages 51 standards and guides that address nuclear safety-related electrical equipment. DOE has cited many of these standards in its own directives and standards, and the Nuclear Regulatory Commission has explicitly endorsed most of these standards. The Board's staff team encourages DOE federal and contract employee attendance at these activities.

DOE contractor personnel regularly attend the Power and Energy Society Industrial Application Society conferences, in which the theory and practice of electrical engineering concerning cable maintenance and condition monitoring is a standing topic. Their participation is an invaluable asset to the DOE complex and should be continued.

Maintenance Strategy. "Run to failure" is a maintenance strategy that forgoes preventive maintenance and relies only on correcting failures as they occur in a system. Practically every electrical system maintenance program includes elements of run to failure because maintaining certain equipment requires significant effort, interruption to operations, and specialized test equipment. Each of the four sites reviewed apply a run to failure approach on some electrical cabling, particularly on cables installed underground.

Interconnected electrical power systems harbor inherent vulnerabilities that can lead to electrical power interruptions. This overview highlights key areas of concern, such as the risk-laden 'run to failure' approach employed in cabling, which significantly enhances the probability of cascading faults—often overlooked in standard safety protocols. Additionally, the dynamics of fault currents are critical; transient surges can exacerbate existing vulnerabilities in cables, with potential damage largely dependent on the electrical characteristics relative to circuit breaker specifications. Moreover, the ramifications of cable failures are considerable, capable of inducing systemic power losses and damage to connected apparatus. There are ongoing challenges in accurately modeling and predicting such failures, emphasizing the necessity for more sophisticated diagnostic and preventive measures in managing electrical power systems.

As such, efforts to reduce in-service cable failures can greatly decrease the overall risk to other cables and connected components. DOE can evaluate potential cable failures through use of recognized condition monitoring techniques. For example, multiple standards in the IEEE 400 series provide applicable condition monitoring references [3–7] that can help identify the rate of degradation in various types of cabling. IEC/IEEE and NRC regulatory publications also contain some guidance related to condition monitoring for cable insulation systems [8–14].

Cable condition monitoring makes it possible to track and trend the decay of cable insulation. This allows maintenance personnel to repair or replace cables in scheduled outages prior to an in-service failure. Although these monitoring techniques are more invasive and time-consuming than visual inspections, they can significantly reduce the likelihood of cable failures.

Best Practices—There are other ways to minimize the impact of in-service cable failures. For critical and difficult to maintain equipment, the ready availability of essential spare parts and staged work packages can ensure timely corrective maintenance. This allows for the expedited replacement of failed components or system modifications designed to restore power quickly to critical facilities. For example, SRNS utility personnel procured a portable substation with generators that can be quickly deployed in the event of substation failure.

SRS personnel also integrated one condition monitoring technique in the maintenance for specific essential power cables. For this case, SRS personnel conducted insulation resistance and tan-delta[2] tests for multiple underground power cables. The test results showed that most cables had sufficient margin to continue operation with monitoring, but the test identified a few cables for replacement at the next supply transformer outage. In addition, as part of an effort to identify potential weaknesses in electrical distribution, SRNS personnel performed a site-wide electrical power failure analysis[3] and identified a series of direct-burial cables that represented an elevated risk of failure. SRNS personnel analyzed these cables using the tan-delta technique and flagged several marginal cables for continued monitoring.

LANL and SRS have adopted improvement strategies that build on the current maintenance practices to mitigate the impact of cable failures and reduce the downtime involved in specifying replacement cables for each voltage and amperage requirement. This is a proactive approach that ensures replacement components are quickly procured when needed. Both sites have adopted generic technical specifications for their electrical distribution cabling and splices that meet this level of preparation. The specifications are well-detailed, organized, and designed for rapid procurement in case of an in-service cable failure.

Aboveground Cable Maintenance. The staff team found reasonable procedures in place to maintain overhead or aboveground cables at all four sites reviewed. These procedures

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[2] Tan-delta is a nondestructive diagnostic test used to determine the condition of cable insulation. Expressed as a percentage, it is fundamentally the tangent of the ratio of the insulation resistive current over its capacitive current.
[3] In 2021 SRNS personnel identified medium-voltage, direct burial cables as the primary concern, given their age and the labor necessary to replace them upon failure. As a result, SRNS personnel tested the condition of these cables in F, B, and G Areas using very low frequency tan-delta tests. Overall, the cable measurements indicated good insulation health, but there were a few cables that warranted retesting in five years. SRNS engineering personnel committed to those retests.

include checking cables visually for cleanliness and abnormal conditions, monitoring mechanical connections, pole integrity, and vegetation encroachment. These sites use thermal imaging in addition to visual checks, although this was not universally implemented.

Best Practices—The Hanford Site had the most well-documented utility pole inspection program and for many years has been actively replacing suspect poles as they are identified. The other sites do inspections but could improve the formality of documenting performance. NNSS personnel also discussed an improvement to the NNSS overhead cable visual inspection program. NNSS has implemented a hands-on[4] inspection performed every five years. This additional inspection greatly increases the likelihood that NNSS personnel will detect mechanical degradation (e.g., loose supports, damaged connectors) before such degradation has a chance to propagate and lead to equipment failure.

Potential Improvements—Adding a written requirement for thermal imaging of connections and suspect equipment, as well as periodic "hands-on" inspections, would greatly increase the effectiveness of visual inspections. Making such inspections more universal would increase their effectiveness in detecting system deterioration. Thermal imaging procedures for most sites omitted recording two key measures: (1) the ambient temperature and (2) the electrical load of the cable at the time of the measurement. This additional data would improve the accuracy of trending analyses of temperatures versus time.

Underground Cable Maintenance. None of the four sites had uniform preventive maintenance schedules for underground low- and medium-voltage cables. However, it is important to note that the amount, type, and installation method of underground cables vary significantly. Accordingly, sites can make valid engineering arguments for running certain cable types to failure in lieu of hazardous or ineffective maintenance.

For underground cables, visual inspections and thermal imaging are the most used inspection methods and do offer valuable insights into cable conditions. However, the efficacy of these methods is limited because most of the cable length is not readily accessible. To determine how the insulation material of the cables is holding up, inspectors must add electrical tests (like measuring insulation resistance) and other condition monitoring techniques.

Best Practices—LANL utility personnel perform annual visual checks and use thermal imaging on all medium-voltage cables and for the vaults the cables run through. SRS, having largely direct-burial cable, focuses on tan-delta testing to monitor the condition of cables it considers high-risk due to their critical roles and replacement concerns.

Potential Improvements—Uniform cable inspections may not be practical for every site, but other condition-based inspection techniques are available and can provide significant value. For instance, after periods of significant rainfall, it is advisable to inspect low elevation

[4] Hands-on visual inspections look for any obvious signs of damage on electrical equipment that includes fraying, discoloration, or melting on wires' connections, insulation, and electrical panels, which could indicate overheating or other electrical faults.

underground cable vaults to verify the effectiveness of their drainage systems. Most underground cables are not designed to operate submerged in water.

Maintenance Backlog and Documentation. None of the sites reviewed carried a significant backlog of preventive or corrective maintenance tasks for their electrical distribution equipment. This is noteworthy and is likely the result of recent efforts to update aging equipment and improve existing maintenance programs.

Best Practices—The maintenance package documentation from Hanford, LANL, and NNSS was thorough and exhibited a level of detail that exemplifies a best practice.

Potential Improvements—While sites effectively document and closely track maintenance tasks related to safety-related equipment, they do not give the same level of attention to general service equipment. A more detailed and careful approach to documentation of maintenance procedures for the general service electrical distribution system merits consideration, given its size and significant role in site operations. Such rigorous documentation is essential for system engineering personnel to track and trend system performance over time.

Tracking Data and Condition Monitoring. When technicians perform corrective activities identified during preventive maintenance, they are typically tackling problems early to prevent the equipment from deteriorating further. However, each of the reviewed sites appears to be missing the crucial step of monitoring how the condition of equipment changes over time. This process can be as straightforward as comparing the thermal images of a specific cable splice year-to-year. During the staff team's interactions, it was clear that site engineers typically make these kinds of comparisons where they have data, but site procedures do not require such comparisons, and the engineers do not formally document them for management.

A well-organized cable management strategy involves choosing the right techniques to monitor the condition of cables and insulation, performing these tests at the suggested intervals, adjusting the test frequency based on how quickly the cables are wearing out, and planning replacements during scheduled downtime based on the observed degradation rates.

Potential Improvements—Sites could conduct a reliability assessment of their entire electrical distribution systems to identify those cables that are at higher risk of failing or that would have the most significant impact to site operations if they did fail. With this information, sites could focus their monitoring efforts on these critical components to decrease the chance of in-service failure. In addition, the electrical industry no longer recommends the use of direct current hi-potential (hi-pot) electrical testing on older cables (more than five years old). While this test is relatively effective in demonstrating cable operation, it can damage cable insulation, thereby shortening the service life of the equipment.

Proposed Plan of Action for Enhancing Cable Maintenance and Safety. To ensure the continued reliability and safety of electrical infrastructure, the staff team compiled the following model for cable maintenance. This plan aims to address the challenges of cable aging, adopt industry consensus standards, establish general maintenance routines, and prepare effectively for cable replacement and in-service failures. It is a compilation of the identified best practices and those improvements the staff team concludes will have the most impact. The plan is provided here for consideration; DOE should lead the development and promulgation of any such uniform guidance for its defense nuclear facilities.

1. **Address Cable Aging**

   a. ***Analyze Critical Infrastructure***: Conduct a thorough analysis of the site distribution system, nuclear facilities, and the requirements of existing and future missions to pinpoint critical infrastructure.

   b. ***Create Cable Aging Management Guidelines***: Develop a set of guidelines focused on the management of cable aging, aiming to protect vital infrastructure.

   c. ***Employ Multiple Cable Testing Techniques***: Use a variety of testing methods to accurately assess the condition of cables across the complex, tailored to specific types of cables, installation type, age, service environment, accessibility, importance to safety and mission accomplishment, etc.

2. **Apply Industry Consensus Standards for Cable Maintenance**

   a. ***Adopt Applicable Guidance***: Integrate existing guidance from relevant IEC/IEEE, NFPA, and NRC regulatory publications into DOE directives.

   b. ***Adopt NFPA 70B-2023***: Implement the latest requirements and guidance from NFPA 70B-2023 for electrical equipment maintenance.

   c. ***Encourage Involvement in Consensus Bodies***: Enhance the involvement of DOE and contractor personnel in consensus bodies, such as IEC, IEEE, and NFPA, to stay at the forefront of new requirements and industry best practices.

3. **Establish General Cable Maintenance Routines**

   a. ***Visual Inspections***: Conduct regular visual inspections of both aboveground and underground cables, including terminations, splices, and supports.

   b. ***Infrared Inspection***: Use thermography to identify potential imperfections in cables, splices, and terminations. Compare images periodically over time to identify any unanticipated temperature increases.

   c. ***Manhole Inspections and Maintenance***: Ensure that the maintenance and inspection of manholes are included as part of routine checks. Consider spot checks after significant weather events in addition to periodic inspections.

   d. ***Nondestructive Electrical Testing***: Employ techniques such as tan-delta and time domain reflectometry for non-invasive electrical testing. As noted above, use a variety of testing techniques as necessary to monitor the types and installations of cabling present.

4. **Prepare for Cable Replacement and In-Service Failures**

   a. ***Minimize the Maintenance Backlog***: Work actively toward reducing the backlog of maintenance and planned replacement tasks.

   b. ***Develop Standard Cable Specifications***: Create standard technical specifications for each cabling type to streamline procurement and replacement processes.

   c. ***Stock Critical Spare Parts***: Maintain an inventory of critical spare parts to enable quick response to failures or maintenance needs.

   d. ***Stage Work Packages***: Pre-plan and prepare work packages for maintenance and replacement activities to expedite repair.

Conclusion. Ensuring the integrity and reliability of electrical power cables requires rigorous maintenance practices. Sites across the defense nuclear complex currently employ many good practices, but opportunities remain for continued improvements. DOE should recognize and uniformly implement these best practices throughout its defense nuclear facilities complex to mitigate the risk of in-service failures of critical safety and general service cables. By ensuring a consistent standard of cable maintenance throughout the complex, DOE can significantly enhance the operational efficacy and safety of its electrical systems.

REFERENCES

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