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A TECHNICAL BASIS FOR GUIDANCE ON LIGHTNING PROTECTION FOR NUCLEAR POWER PLANTS

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ABSTRACT

This paper describes the underlying basis for guidance on the protection of nuclear power systems from direct lightning strikes to facilities and resulting transient effects. Oak Ridge National Laboratory has been engaged by the U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research to develop a technical basis for guidance to address design and implementation practices for lightning protection systems in nuclear power plants (NPPs). Lightning protection is becoming increasingly important given the use of digital and low-voltage-analog systems in NPPs. Although these modern systems have advantages and useful features, they have the potential to be more vulnerable than older, analog systems to the power surges and electromagnetic interference that result when lightning strikes facilities or power lines.

1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) has engaged Oak Ridge National Laboratory (ORNL) to develop a technical basis for guidance that addresses design and implementation practices for lightning protection systems in nuclear power plants (NPPs). Lightning protection in NPPs is becoming increasingly important with the widespread use of digital and low-voltage analog electronic systems. For a variety of reasons, these systems have positive benefits in nuclear power systems; however, because of lower internal operating voltages and high internal operating frequencies, they are potentially more vulnerable to lightning-induced transients than are older, analog systems. This paper discusses important issues regarding the protection of nuclear power instrumentation and control (I&C) systems from direct lightning strikes and resulting secondary effects.

The scope of the ORNL technical basis includes protection of the power plant and relevant ancillary facilities, with a boundary beginning at a building's service entrance, including (1) the in-plant electrical distribution system, safety-related I&C systems, and communications within the power plant, as well as (2) other important equipment in remote ancillary facilities that could impact safety. The scope excludes protection of power lines and the plant switchyard. It does not cover testing and design practices intended to protect safety-related I&C systems against the secondary effects of lightning discharges [i.e., low-level power surges and electromagnetic interference (EMI)]. These practices are covered in Regulatory Guide 1.180 (NRC 2000a).

Six Institute of Electrical and Electronics Engineers (IEEE) industry standards are recommended for endorsement to address issues associated with NPP lightning protection. In addition, reference data from several other lightning-related standards are included in the recommendation.

1.1 A Primer on Lightning

Weather experts report that lightning strikes the earth 100 times each second around the world and that 16 million thunderstorms occur worldwide each year (“When Lightening Strikes,” 2000). The regions most prone to this violent weather are those where very moist and unstable air masses move through year-round (e.g., regions in close proximity to the Gulf of Mexico and the Atlantic Ocean) (Schill, 1996). Some additional facts about lightning are shown in Fig. 1 (LPI, 1999; Uman, 1984).

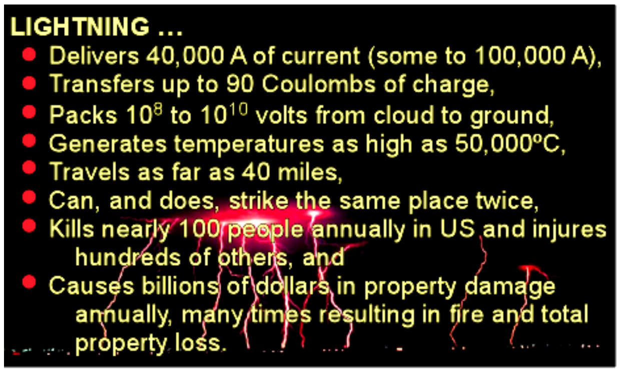

Fig. 1 Lightning facts.

Some U.S. Department of Energy nuclear facilities in the Southeast have been known to experience more than 75 lightning-related occurrences over a 5-year period, while others in the West escaped with just 9 over the same period (Schill, 1996). In the nuclear power industry, a lightning strike at the Diablo Canyon Nuclear Power Plant on September 22, 1999, caused a reactor trip (*Tenth Annual Report on the Safety of Diablo Canyon Nuclear Power Plant Operations*, July 1, 1999–June 30, 2000). In addition, a reactor at the Rivne Nuclear Power Plant in Ukraine automatically shut down on August 18, 2000, after it was struck by lightning (“Nuclear Reactor Shuts Down after Lightning Strike,” 2000). Lightning is a serious threat, and protection is essential to avoid malfunctions and upsets that, in turn, lead to reactor trips and unsafe conditions. It is generally believed by some that increases in global warming will lead to more frequent and severe storm activity.

1.2 Lightning Effects and Propagation

Procedures and requirements to prevent lightning-induced transients from propagating to and interfering with safety-related I&C systems contribute to the assurance that structures, systems, and components important to safety are designed to accommodate the effects of environmental conditions (i.e., remain functional under all postulated service conditions). The most important deleterious effects of lightning-induced transients are that systems related to safety are either rendered inoperable or are triggered to spurious operation, and that fires are started, which damage crucial equipment or impede safety-related functions.

The scope of our investigation includes medium- and distribution-level voltages within the nuclear plant that power safety-related I&C systems and components. The boundary as far as lightning guidance is considered is at the interface between the substation and the building. For example, general protection of the substation against damage from lightning would not be a part of the investigation.

Electrical distribution from off-site power through control and safety systems forms a series path through the plant, as shown in Fig. 2. Equipment housed in the plant building structures is protected from direct lightning strikes; however, propagation of lightning-induced transients may follow a variety of paths from the switchyard to sensitive electronic components owing to its high-voltage, high-current, and high-frequency characteristics. IEEE standards related to lightning protection have overlapping applicability to NPP systems; they are shown in Fig. 2.

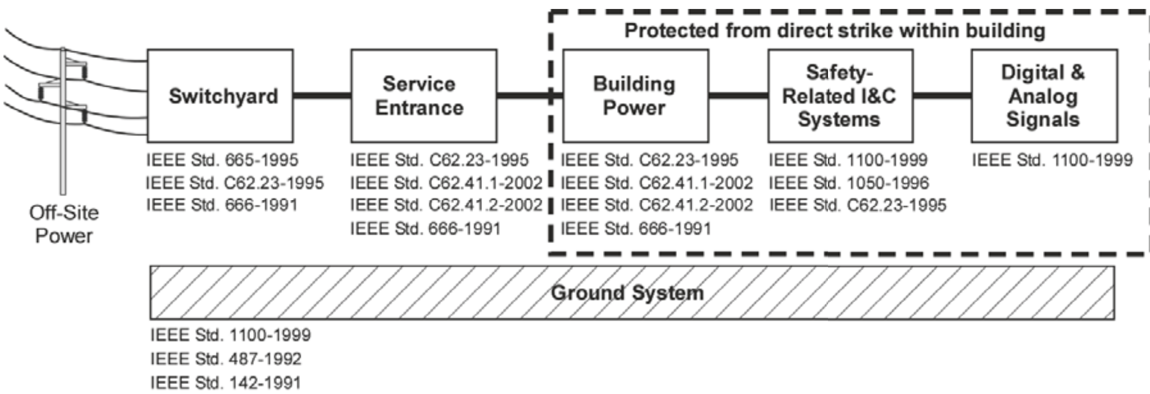

Fig. 2 Applicable IEEE standards associated with plant components.

A lightning strike generates transients that propagate through plant electrical distribution and are coupled into equipment by a variety of mechanisms, such as direct coupling through conductors, magnetic induction to nearby conductors, capacitive coupling, direct arc-over to lower-potential points, and ground potential rise (GPR). Equipment that can be affected ranges from power-level devices (e.g., motors, circuit breakers, and transformers) to electronic I&C systems. I&C systems are particularly vulnerable to transients, which can enter through power supply connections and sensor signal paths. The unique feature of a lightning transient is that it does not interact with facilities and components in a consistent manner.

The possible consequences of a lightning strike are summarized and generalized in Fig. 3. Lightning induces transient currents and voltages that produce a direct primary effect on plant systems and components. As a result, system and component responses include tripping of protective relays, spurious response, component failure, and fire. Ultimately, a significant action results, such as reactor trip, spurious safety actuation, blockage of safety actuation, or loss of fire protection. No experiential data from plant records have shown an example of blocked safety system actuation, although some lightning events have come close to such a response.

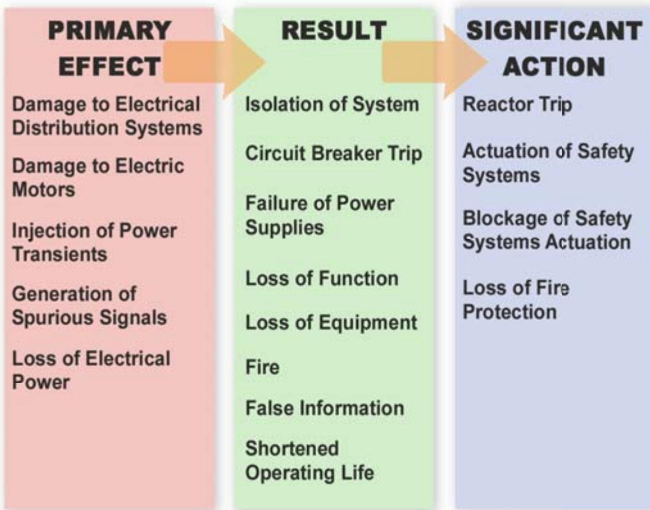

Fig. 3 Effects of lightning transient on plant systems.

2. LICENSEE EVENT REPORT DATA

A previous examination of the NRC licensee event report (LER) database included 174 events with lightning-related incidents at NPPs from the period 1980 to 1991 (Rourk 1992, 1994). The conclusion of that examination was that the most significant impact on plant operation that may be lightning-caused is from the effects of local strikes, such as GPR. High-frequency voltage transients created on the transmission system by lightning do not cause significant equipment misoperation or damage because they are greatly attenuated by redundant levels of protection before reaching the low-voltage service level. Based on the analysis of LER data, Rourk (1992 and 1994) concluded that local strikes do not appear to create a significant risk to plant safety.

A second LER search was made by the ORNL team to determine the effects of lightning over the next 10 years, 1990 to 2000. Table 1 summarizes the categories of such lightning-induced events. Nineteen plants reported a total of 30 events that listed lightning as the causal agent. Eleven events involved reactor trips, 9 involved a loss of power or other action that caused the backup diesel generator to start, 2 each involved ventilation or containment isolation, and 6 others were miscellaneous events.

It appears significant that while less than 20 percent of the NPPs reported lightning-induced LERs, several of those plants recorded two or three during the 1990s. This issue should be pursued to determine whether these plants have special susceptibilities or whether they fall within the expected norms, given their local weather conditions. Similar discrepancies between lightning events at nuclear power plants were observed in a study of four plants by Entor Corporation (Pielage, 1981). The differences were attributed to the degree of adherence to lightning protection practices prescribed in National Fire Protection Association (NFPA) 78 (now superseded by NFPA 780) (2001).

Table 1 Categorization of lightning-induced LERs from 1990 to 2000.

Event	Frequency
Reactor trip/scram	11
Loss of power/voltage sag/diesel generator start	9
Ventilation isolation	2
Containment isolation	2
Other	6
All events	30

3. REVIEW OF APPLICABLE STANDARDS

A few key standards taken together cover the basics of lightning protection in power generation stations. These standards cover external grounding grids and lightning protection (IEEE Std. 665), conductor egress and internal grounds (IEEE Std. 1100, IEEE Std. 1050, and IEEE Std. 666), and the proper selection and use of surge protective devices (SPDs) (IEEE Std. C62.23 and IEEE Std. C62.41). In addition to these standards, several other standards address key concerns that are not completely covered by the aforementioned standards. A list of the 16 standards judged most applicable to lightning protection for NPPs is given in Table 2.

IEEE Std. 665 was chosen as the primary standard for endorsement because of its focus on grounding in generation stations. It draws from IEEE Stds. 80, 81, and 81.2 for measurement and calculation of soil resistivity and grid currents. IEEE Std. 665 also draws from standards that focus on the grounding of specific types of systems; these include IEEE Std. 142 for commercial power systems, IEEE Std. 1050 for I&C systems, IEEE Std. C37.101 for generator grounds, and IEEE Std. C62.92 and IEEE 666 for neutral grounding. Other standards highlight some issues, such as conductor egress and SPDs, more thoroughly than IEEE Std. 665 and are included as references.

The six primary standards recommended for endorsement by this study are listed in Table 3 with comments regarding their applicability. In addition, referenced material from other standards is included in the recommendation.

Table 2 The 16 standards judged most applicable to lightning protection for NPPs.

Standard number	Standard title
IEEE Std. 80-2000	IEEE Guide for Safety in AC Substation Grounding (ANSI)
IEEE Std. 81-1983	IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System (ANSI)
IEEE Std. 81.2-1991	IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems
IEEE Std. 142-1991	IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems *(IEEE Green Boo*k)
IEEE Std. 367-1987	IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault (ANSI)
IEEE Std. 487-2000	IEEE Recommended Practice for the Protection of Wire-Line Communication Facilities Serving Electric Power Stations (ANSI)
IEEE Std. 665-1995 (reaffirmed 2001)	IEEE Guide for Generating Station Grounding
IEEE Std. 666-1991	IEEE Design Guide for Electric Power Service Systems for Generating Stations
IEEE Std. 1050-1996	IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations (ANSI)

Table 2 (continued).

Standard number	Standard title
IEEE Std. 1100-1999	IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (IEEE Emerald Book) [ANSI]
IEEE Std. C37.101-1993	IEEE Guide for Generator Ground Protection (ANSI)
IEEE Std. C57.13.3-1983	IEEE Guide for the Grounding of Instrument Transformer Secondary Circuits and Cases (ANSI)
IEEE Std. C62.23-1995	IEEE Application Guide for Surge Protection of Electric Generating Plants (ANSI)
IEEE Std. C62.92-1987 (reaffirmed 1993)	IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part I-Introduction (ANSI)
IEEE Std. C62.41-1991 (R1995)	IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits
NFPA 780-2001	Installation of Lightning Protection Systems

Table 3 Top standards related to lightning protection.

Standard	Applicability
IEEE Std. 665-1995 (R2001)	Recommended for endorsement as the primary guidance for lightning protection in nuclear power plants. It focuses on the direct effects of lightning strokes and draws heavily from ANSI/NFPA 780, *Installation of Lightning Protection Systems*. ANSI/NFPA 780 is a widely accepted standard for lightning protection of most types of structures, but it specifically excludes power generation plants.
IEEE Std. 666-1991	Recommends neutral grounding practices for the grounding of generating station auxiliaries, insulation levels for protection against voltage surges from lightning transients, and surge protection for transformers, switchgear, and motors.
IEEE Std. 1050-1996	Covers the specific components necessary to prevent damage to I&C equipment that can be caused by the secondary effects of lightning.
IEEE Std. 1100-1999	Covers more completely possible conflicts between the grounding needs of I&C systems and those of other electronic systems (known as balance-of-plant equipment).
IEEE Std. C62.23-1995 (R2001)	Consolidates many electric utility power industry practices, accepted theories, existing standards/guides, definitions, and technical references as they pertain to surge protection of electric power generating plants.
IEEE Std. C62.41-1991 (R1995)	Gives general guidance on the selection of surge-protection devices that can reduce the effects of lightning-induced surges to levels that electronic equipment can withstand.

4. RESULTS

Experience shows that all nuclear power facilities should have a well-designed, -installed, and -maintained lightning protection system (LPS), which traditionally refers to an external system consisting of air termination (lightning rods), down-conductors, and an earth grounding system. Additionally, facilities containing vulnerable electronic equipment (such as I&C and other equipment that interconnects multiple signal and communication paths) require an internal grounding system that addresses cable routing and bonding to the earth grid at key locations. The best-known source of information about LPS design guidelines in use today is ANSI/NFPA 780 (2001), which is the foundation document for protecting facilities from direct lightning strikes. Almost all lightning protection guidance standards reference ANSI/NFPA 780. However, while ANSI/NFPA 780 gives good guidance and philosophies on lightning protection, it has a disclaimer concerning electric power generation facilities:

> **A-1-1.2** Electric generating facilities whose primary purpose is to generate electric power are excluded from this standard with regard to generation, transmission, and distribution of power. Most electrical utilities have standards covering the protection of their facilities and equipment. Installations not directly related to those areas and structures housing such installations can be protected against lightning by the provisions of this standard.

Thus, while the concepts of the standard can be adopted, ANSI/NFPA 780 itself cannot be endorsed as primary guidance for NPPs. It can, however, be used as a guide to ensure all of the key elements of lightning protection are covered when other standards are endorsed.

Key common sense guiding principles for protection against lightning taken from the standards involve defense in depth and are almost always applicable:

1. If it is metal and is not intended to carry current, ground it.
2. If it is metal and is intended to carry current, and it is outside a building, protect it with taller grounded structures.
3. If it is inside a building, surge-protect it.
4. If it is a sensitive electronic circuit, build it to withstand whatever gets past the barriers 1–3, including transients carried through low-level instrumentation wiring.

The seven themes listed in Table 4 represent a practical approach to meeting the guiding principles and determining whether or not an NPP has sufficient protection against lightning.

From a review of the applicable standards, we envision that IEEE Std.. 665-1995 (R2001) leads the other standards and gives guidance on protection of the whole facility. IEEE Std. 666-1991 addresses neutral grounding and insulation. IEEE Std.. 1100-1999 addresses filtering and grounding of service lines and other conductors that egress the LPS boundary. IEEE Std. 1050-1996 applies to grounding and filtering I&C equipment inside a facility. Finally, we use IEEE C62.23 and IEEE C62.41 to address

Table 4 Key lightning protection themes.

	Theme
1.	Overall grounding plan
2.	Quality of LPS
3.	Quality of filtering and grounding of conductors that egress LPS
4.	Cable routing within the facility
5.	Correct selection and placement of SPDs throughout facility
6.	Grounding of the I&C components
7.	Protection of equipment from electromagnetic surges

surge-protection devices. While these standards address the major issues, further guidance on secondary issues can be found in the other standards called out in Table 2.

Data from the first LER examination period (1980–1991) indicate a probability of 3.2×10^4 per reactor year for a loss of fire protection with simultaneous fire due to a lightning strike. The core damage probability (CDP) is estimated to be two orders of magnitude less than that of the initiating event frequency, or 3.2×10^{-6} per reactor year. Although this CDP value is small and may tempt analysts to conclude that lightning poses no safety concern, other factors should be considered. For example, electronic systems are being designed with increased intelligence and are potentially more vulnerable to electrical transients and EMI (NRC, 2000b; Ewing and Antonescu, 2001). LER data are based on operating plants with older, analog electronic and electromechanical systems. No data are available from plants with digitally-based electronic systems. Lightning transients have the potential of generating a cascade of destructive events that generate spurious I&C signals while simultaneously damaging plant components. For example, lightning-induced electrical transients can erroneously start subsystems and initiate fires. A particular event sequence that illustrates the point occurred at a nuclear power station in June 1991 (NRC, 1991). Plant operating power was 89 percent of full power prior to the event. The event was initiated by a lightning strike (possibly multiple strikes) that disabled both off-site power sources, started a transformer fire, and disabled communication systems. The turbine and reactor automatically tripped at the event onset. The cascade of failures delayed restoration of off-site power for about 12 hours.

5. CONCLUSIONS

Six IEEE standards are recommended for endorsement to address issues associated with protecting NPPs and their equipment against lightning. In addition, referenced material from other standards is included in the recommendation.

Although an analysis of lightning-induced events at NPPs does not conclusively indicate imminent danger from lack of protection guidance, events at several facilities suggest the need for more guidance for new facilities. NPPs built in the 21st century will no doubt employ state-of-the-art electronics having a multiplicity of signal and communication interconnections, with their attendant sensitivity to electromagnetic interference. It would, therefore, be prudent to develop an appropriate technical basis for lightning protection practices.

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REFERENCES

ANSI/NFPA (American National Standards Institute/National Fire Protection Association) 2001. *Standard for the Installation of Lightning Protection Systems*, ANSI/NFPA 780-2001.

Ewing, P. D. and C. Antonescu 2001. "EMI/RFI and Power Surge Withstand Guidance for the U.S. Nuclear Regulatory Commission," CNRA/CSNI Workshop, Hluboka nad Vltavou, Czech Republic, Committee on Nuclear Regulatory Activities and the Committee on the Safety of Nuclear Installations. Programme Committee and Session Chairmen will publish the summary report, Hluboka nad Vltavou, Cz. 2001.

LPI (Lightning Protection Institute) 1999. "Lightning and Lightning Protection Systems," http://www.lightning.org/protect.htm.

NRC (U.S. Nuclear Regulatory Commission) 1991. *Loss of Offsite Power Event*, NRC Special Inspection Report 50-29/91-09, July.

NRC (U.S. Nuclear Regulatory Commission) 2000a. *Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems*, Regulatory Guide 1.180, January 31.

NRC (U.S. Nuclear Regulatory Commission) 2000b. *Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants*, NUREG/CR-6431, January.

"Nuclear Reactor Shuts Down after Lightning Strike," Ananova, http://www.ananova.com/news/story/sm_39104.html, August 18, 2000.

Pielage, H. W. 1981. *Lightning Problems and Protection at Nuclear Power Plants*, NSAC-41, Nuclear Safety Analysis Center, Electric Power Research Institute, December.

Rourk, Chris 1992. *Report on the Sources and Effects of Electrical Transients on the Electrical Systems of Commercial Nuclear Power Plants*, Internal Engineering Report, Engineering Issues Branch, Division of Safety Issues Resolution, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, September.

Rourk, Chris 1994. “A Review of Lightning-Related Operating Events at Nuclear Power Plants,” *IEEE Transactions on Energy Conversion*, 9(3), 636–641 (September).

Schill, Karin 1996. “SRS Frequent Lightning Target,” *Augusta Chronicle* Online, http://www.augustachronicle.com/headlines/091796/srs_lightning.html, September 16.

Tenth Annual Report on the Safety of Diablo Canyon Nuclear Power Plant Operations, July 1, 1999–June 30, 2000.

Uman, M. A, 1984. *Lightning*, ISBN 0-486-64575-4, Dover. General Publishing Company, Ltd., 30 Lesmill Road, Don Mills, Toronto, Ontario, “When Lightning Strikes,” *Emergency Essentials*, http://www.beprepared.com/Articles/Lightn.html, June 15, 2000.