Mitigating Lightning Hazards

Lawrence Livermore engineers' investigations of lightning, its hazards, and how to protect against them have led to the development of guidance to aid in dealing with the effects of lightning on DOE facilities, particularly those where nuclear and high-explosive materials are handled and stored. Our guidance document provides risk managers with a unified and graded method for attaining lightning safety.

THE awesome sound and light show of a thunderstorm has always been a source of fear and wonder. At any time some 2,000 thunderstorms are in progress around the globe, causing the majority of forest fires and, in the U.S. alone, hundreds of millions of dollars in property losses. Lightning is also the leading weather-related killer in the U.S., causing from 100 to 200 deaths annually.

Despite these facts, most engineers and architects have at best only a rudimentary knowledge of lightning and protection methods, says Richard Hasbrouck, LLNL engineer in the Defense Sciences Engineering Division within Electronics Engineering. A lightning expert, Hasbrouck is co-author of the draft "Lightning Hazard Management Guide" for the Department of Energy.

"Lightning and its associated effects are a mystery to many engineers because these subjects are not included in most engineering curricula," he says. Department of Energy managers whose job it is to assure the mitigation of natural phenomena hazards (such as lightning) for an operation or facility must contend with a hodgepodge of scientific data related to lightning, commercial products (some of questionable worth), unrealistic building codes, folklore, and half-truths. As a result, he says, many facilities, instruments, and control systems are vulnerable to damage or lightning-induced upset or malfunction.

Hasbrouck points out that earlier generations of electrical and electronic systems and components used vacuum tubes, relays, and analog control and computation devices that were intrinsically more robust against the effects of lightning than are today's solid-state, microprocessor-based systems. Brief overvoltages caused by lightning and manmade transient voltages can immediately destroy low-power, solid-state components such as computer chips or weaken them to the point that they fail months after a lightning event.

DOE facilities' vulnerability to lightning was underscored last summer by Michael Kelly, a high school electronics teacher participating in LLNL's Summer Research Intern Program. Kelly analyzed reports of 365 lightning-related occurrences at DOE facilities since October 1990 and found that lightning caused a variety of physical damage and alarm system malfunctions. His report draws attention to numerous failures of lightning protection devices, alarm systems, and backup generator systems.

Unified Approach Needed

No single document presents a unified approach to lightning safety and protection, Hasbrouck notes. The latest version of the *U.S. National Fire Protection Association Lightning Standard* only briefly references surge suppression. *The Standard for Safety Lightning Protection Components* recently issued by Underwriters Laboratories provides only general information. What's more, says Hasbrouck, the Department of Defense *Ammunition and Explosives Safety Standards* are very general and offer neither guidance nor applicable references. The recently released revision of the *International Lightning Protection Standard* is significantly ahead of U.S. standards.

In response, in 1993 Hasbrouck and fellow engineer Kartik Majumdar proposed developing a guidance document to help DOE managers in assessing the lightning risks associated with any facility and determining the most effective means for mitigating the hazard. That year, the two engineers organized a lightning workshop in Florida sponsored by DOE's Office of Risk Analysis and Technology. Attendees from DOE and its contractors, the Nuclear Regulatory Commission, and other federal government agencies agreed that a comprehensive guidance document on lightning protection was needed as one of a series on natural phenomena hazards mitigation.

Released in draft form in 1995, it is anticipated that the "Lightning Hazard Management Guide for DOE

Striking Facts about Lightning

Cloud-to-ground lightning is the best understood—and most dangerous—type of lightning. It comes in two varieties, positive and negative. Here we will discuss only negative lightning.

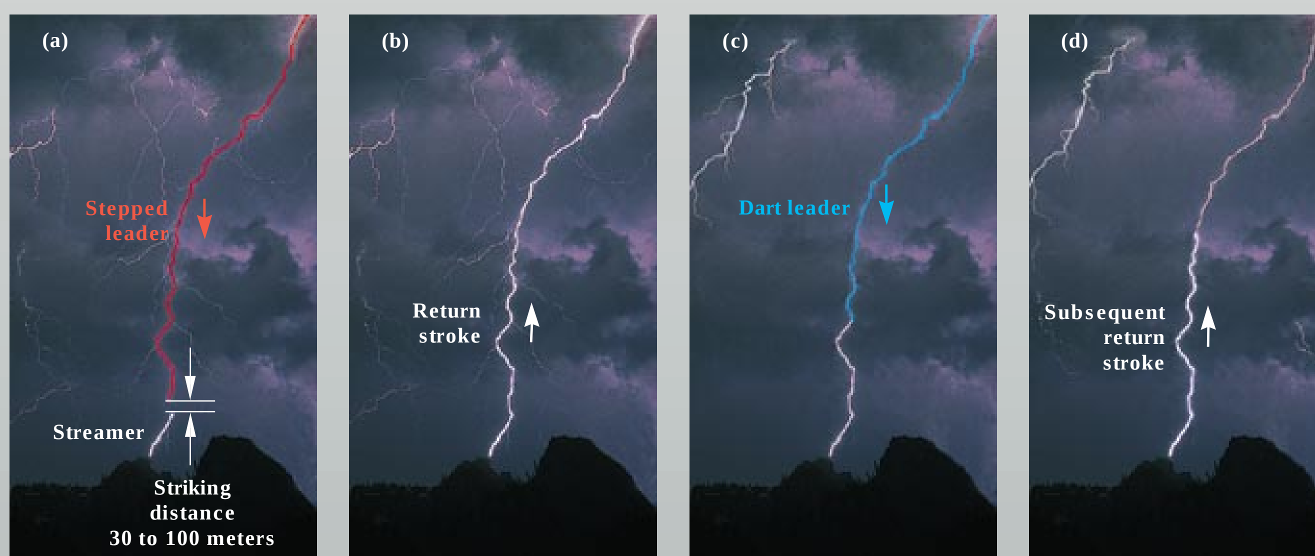
As with other types of lightning, negative cloud-to-ground lightning begins when complex meteorological processes, driven by powerful updrafts, cause a tremendous electrostatic charge separation to build up within a thunderstorm cloud. Typically, the bottom portion of the cloud is negatively charged. When voltage levels of about 50 to 100 million volts are reached, air can no longer provide insulation, and electrical breakdowns called intracloud lightning take place within the cloud.

Some 10 to 30 minutes after the onset of intracloud lightning, negative charges called "stepped leaders" emerge from the bottom of the cloud, moving toward the earth in 50-meter-long steps at speeds of 0.03 to 0.07% of the speed of light (about 100 to 200 km/s). (See the illustration below.) The leaders carry the full voltage of the cloud's negative charge center and create an ionized channel. As the leaders near the Earth, their strong electric field causes streamers of positively charged ions to develop at the tips of grounded pointed objects. These objects may include pine needles, blades of grass, towers, raised golf clubs, and human heads.

These positively charged streamers flow upward under the strong influence of the negatively charged stepped leader.When the distance between a stepped leader's tip and one of the streamers becomes small enough (known as the striking distance, from 30 to 100 meters), the intervening air breaks down and the leader is joined to Earth via the streamer. Now a pulse of current known as a "return stroke" ranging from thousands to hundreds of thousands of amperes moves at one tenth to one third the speed of light (35,000 to 100,000 km/s) from Earth through the object from which the streamer emanated and up the ionized channel to the charge center within the cloud, temporarily neutralizing it. An ionized channel remains in the air, and often, additional negative charges, called dart leaders, will quickly move down this path, resulting in subsequent return strokes. It is this multiplicity that causes the flash to appear to flicker. After 30 to 60 seconds, the neutralized center recharges and is ready to produce another flash.

The return stroke's extremely high temperature (30,000 kelvin) creates the highly visible lightning channel and instantly turns moisture into steam, producing the associated thunder. The entire event, often consisting of multiple return strokes and typically lasting up to 1 second, is referred to as a lightning flash.

Most direct damage results from the heavy return stroke current that produces a large temperature rise in the resistance of the channel through which the charge travels or from arcing at the point of attachment. When arcing takes place in a combustible or explosive environment, fire or an explosion can result. If the lightning current is carried by an enclosed conductor (e.g., within a jacketed cable, through a concrete wall, or beneath a painted surface), entrapped moisture is turned into high pressure steam, which can cause the cable or painted object to burst, the wall or a tree to explode, or the shoes to be blown off the damp feet of a person struck by lightning.



Artist's rendering of a cloud-to-ground lightning flash from (a) development of the negatively charged stepped leader and positively charged streamer through (b) the return stroke followed by (c) a dart leader resulting in (d) a subsequent return stroke.

Facilities" will be used by new facilities within DOE, other government agencies, and the private sector for determining design requirements as well as for evaluating existing lightning safety and protection systems.[1]

"Lightning Hazard Management Guide" presents a unified approach to lightning safety and protection that combines hazard identification and facility categorization with a new concept—the Lightning Safety System. The Lightning Safety System integrates four lightning safety elements usually addressed as separate topics: a warning system, a warning response plan, a protection system, and a safety system certification plan. Hasbrouck notes that the extent to which each element is implemented at a particular site depends upon the mission of the facility; the element's impact upon the safety of workers, the public, and the environment; and the cost versus benefit of the element's implementation.

"This flexibility allows managers to apply a graded approach in determining the most effective mix of hardware, software, and procedures to solve their particular problem," he says.

Hasbrouck has researched lightning and its effects for more than a decade. He carried out rocket-triggered lightning tests and was responsible for the design of the Lightning Invulnerable Device System to protect nuclear explosive test device systems from lightning.[2,3] He has also written (and presented) a tutorial (*Lightning—Understanding It and Protecting Systems from Its Effects*[4]) based on classic texts, current literature, and LLNL experiments.

The work of Hasbrouck and his colleagues is part of a larger LLNL effort to better understand the effects of lightning. Other members of the Laboratory's Defense Sciences Engineering Division have long worked with people in LLNL's weapons program and with experts from Sandia and Los Alamos National Laboratories to ensure that nuclear warheads are protected from lightning (see the box on p. 9). At the same time, LLNL atmospheric investigators have been working to determine lightning's contribution to acid rain. One group is also studying massive, high-altitude, cloud-to-sky lightning-related events called "sprites."

Huge Electrical Discharge

Hasbrouck explains that lightning is an electrical discharge of immense proportions* that accompanies not only thunderstorms, but also volcanic eruptions, snow and dust storms, and surface nuclear detonations. At the mid-Northern latitudes, some 80% of lightning occurs within clouds (intracloud). About 20% of all lightning is cloud-to-ground, while an extremely small percentage is cloud-to-sky and between clouds. (Figure 1)

Cloud-to-ground lightning represents the greatest threat to people, structures, systems, and components. It can be either positive or negative. The vast majority of cloud-to-ground lightning is negative, that is, it transfers negative charge to Earth via a channel—the stepped leader—that emanates from the lower portion of a storm cloud and moves toward the Earth. Once the leader contacts Earth, positive charge moves back up the negatively charged channel, neutralizing it and its source, a negative charge center in the cloud.

During a positive lightning event, on the other hand, a large quantity of positive charge is transferred to the Earth. Negative charges move back up the lightning channel to the thunderstorm cloud, temporarily neutralizing a highly positive-charged region within the cloud. Positive lightning occurs much less frequently than negative lightning and most often toward the end of a thunderstorm, originates in the upper part of a thunder cloud rather than in the lower part, and can be more severe in its effects than negative lightning.

A single lightning event, called a flash, typically lasts for many hundreds of milliseconds (see the box on p. 6); intense thunderstorms can produce several thousand cloud-to-ground flashes. For each discharge, a tree-like streamer (or leader) carries charge toward the ground until the "striking distance" (30 to 100 meters) is reached. The oppositely charged return stroke transforms electrostatic potential energy into electromagnetic energy (radio and light waves), heat, and acoustic energy (thunder).

As delineated in the draft DOE guide, lightning hazard identification considers the severity of the hazard and its likelihood of occurrence. The severity of a flash is defined by the peak amplitude of its return stroke current, its rate of rise, and the amount of charge transferred, while the probability of an object being struck is the product of the local ground-flash density times its lightning-attractive area.

The guide recommends that managers combine a timely and credible threat warning system with suitable lightning protection methods. The warning system should provide an alert when a lightning threat is identified and an alarm when lightning is imminent. A suitable plan for responding to a warning should also be implemented.

Cloud-to-ground lightning occurs randomly, making it impossible to

* The average electrical discharge of lightning is about 15 coulombs; the highest charge transfer is estimated to be about 350 coulombs. One coulomb is the equivalent to the electric charge of 6.24×10^{18} electrons.

Figure 1. An artist's depiction of the four basic kinds of lightning: (a) cloud-to-sky lightning (sprites), (b) cloud-to-ground lightning, (c) intracloud lightning, and (d) intercloud lightning.

accurately predict when and where it will strike. However, lightning announces itself in several ways. A thunderstorm's cloud-to-ground lightning provides some advance warning if its visible, audible, and electromagnetic signals are detected. Ideally, a system designed to acquire and display warnings needs to incorporate one or more direct weather observations, National Weather Service reports (including information from the National Lightning Detection Network), flash detectors, and electric field sensors.

Strikes Are Inevitable

In the lightning guide, the authors emphasize that despite nonscientific commercial claims to the contrary, the charge in a thunderstorm can be dissipated only by nature's way—the lightning process. Proper lightning protection accepts a strike as inevitable, seeks to provide a controlled path for the current to follow, and minimizes the development of hazardous potential differences.

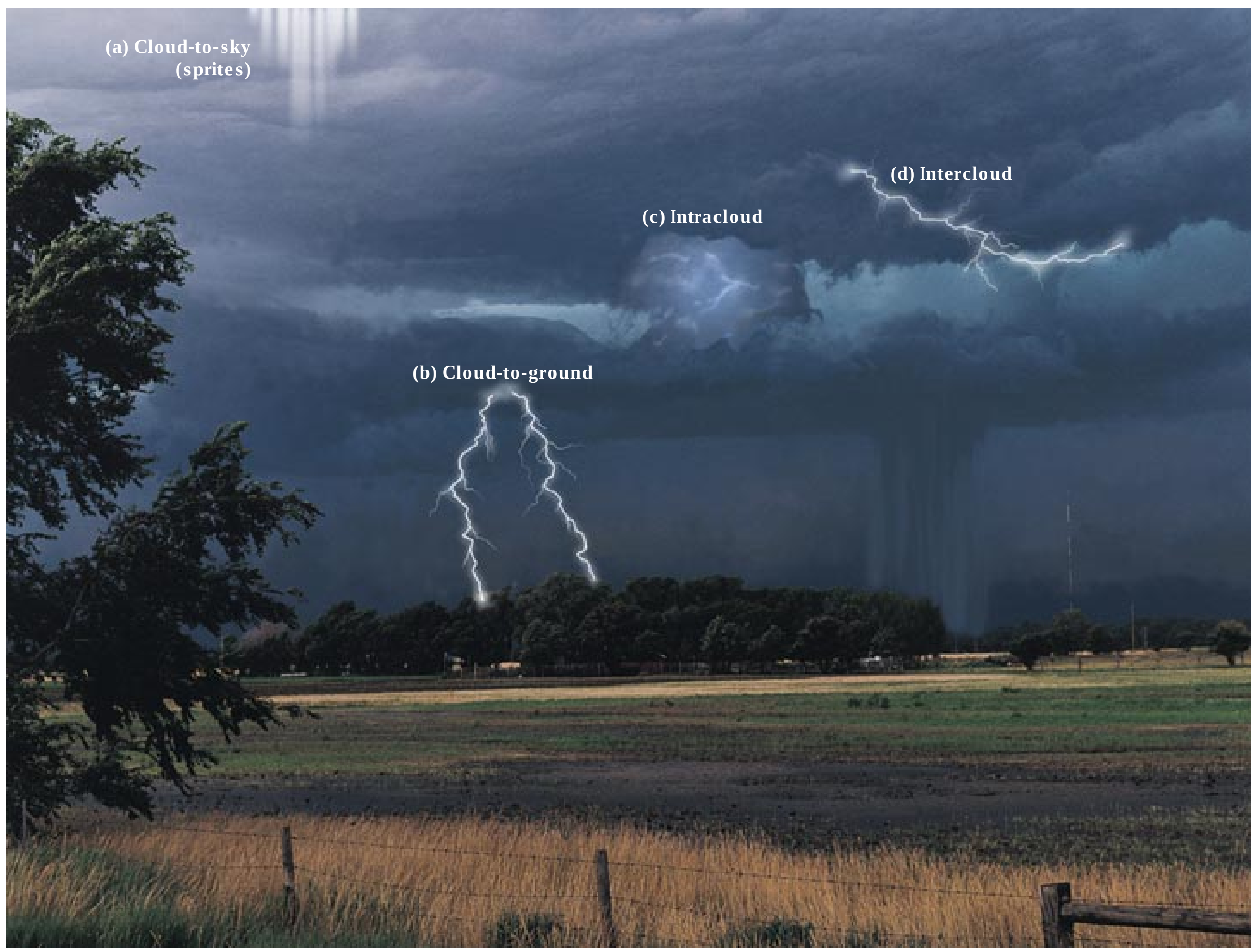


Photo by Treva Carey

"Lightning is a very-large-amplitude current source," says Hasbrouck. This means that the same amount of current will flow, regardless of whether its path is of low resistance (a metal flagpole) or high resistance (a tree). Much of the energy contained in a lightning return stroke is dissipated as heat in whatever path serves as the current-carrying conductor. A good electrical conductor, e.g., metal structure, will experience little more than minor surface pitting where the current enters and exits. Significant damage can result, however, when poor conductors such as a wood-frame building, concrete wall, or tree are struck.

The draft guide presents the "fortress" concept, in which first-level protection of a structure is provided by a lightning grounding system. All electrically conductive paths that penetrate the building (e.g., metallic pipes and vent stacks) are bonded to the lightning grounding system externally at the point of entry. To protect components housed inside, all electrical conductors pass through transient limiters (surge arrestors) located inside the structure as close as possible to the point of entry. Also, limiters are recommended at the power and data input points of individual systems and components.

Using New Testing Methods

Last year, the document got its first real-world application when Hasbrouck engaged LLNL engineer Richard Zacharias and Richard Collier, an elecromagnetics consultant from EMA Inc. with experience using swept-radio-frequency testing for facility lighting studies, to determine the effectiveness of the lightning protection system of the recently completed Device Assembly Facility (DAF) at the Nevada Test Site. The cavernous DAF

Protecting the Nuclear Stockpile from Lightning

The U.S. military and space programs have long respected the potential of lightning to damage or even destroy vital weapons components as well as aircraft and spacecraft. Lightning caused the annihilation of a World War I arsenal in New Jersey, it almost turned the Apollo-12 launch into a disaster, it has been responsible for several aircraft crashes, and it led to the destruction of an Atlas-Centaur launch vehicle in 1987, with its $160-million payload.

The vulnerability to lightning of today's aircraft and spacecraft is greater than in years past because critical airborne systems employ vast numbers of solid-state components that are susceptible to the effects of a lightning strike as well as the associated electromagnetic fields. In addition, new designs increasingly substitute composite materials for metallic surfaces, eliminating what once was, in effect, a flying Faraday cage, that is, an almost complete metal enclosure that houses the aircraft's electrical and electronics systems.

Lawrence Livermore lightning expert Mike Wilson of Defense Sciences Engineering Division notes that for people residing in the San Francisco Bay Area, home of typically five lightning storms a year, damage from lightning may seem a far-fetched threat. However, DOE's Pantex plant, located in Texas, experiences about 60 lightning storms annually, and the threat of lightning igniting some of the propellants and high explosives stored at the plant is a real concern. Indeed, DOE considers lightning a particular risk to operations involving the transport, maintenance, and modification of nuclear devices and their associated non-nuclear explosives.

Wilson says that Livermore engineers have been assessing the potential threats from lightning strikes for more than 15 years as part of the Laboratory's mission to assure the safety of nuclear devices. "We're concerned with all environmental threats to the nuclear stockpile," he says. "Lightning has been considered by some people to be an awesome environmental threat from which nothing could survive. But that's not the case. We just need to understand lightning and protect against it."

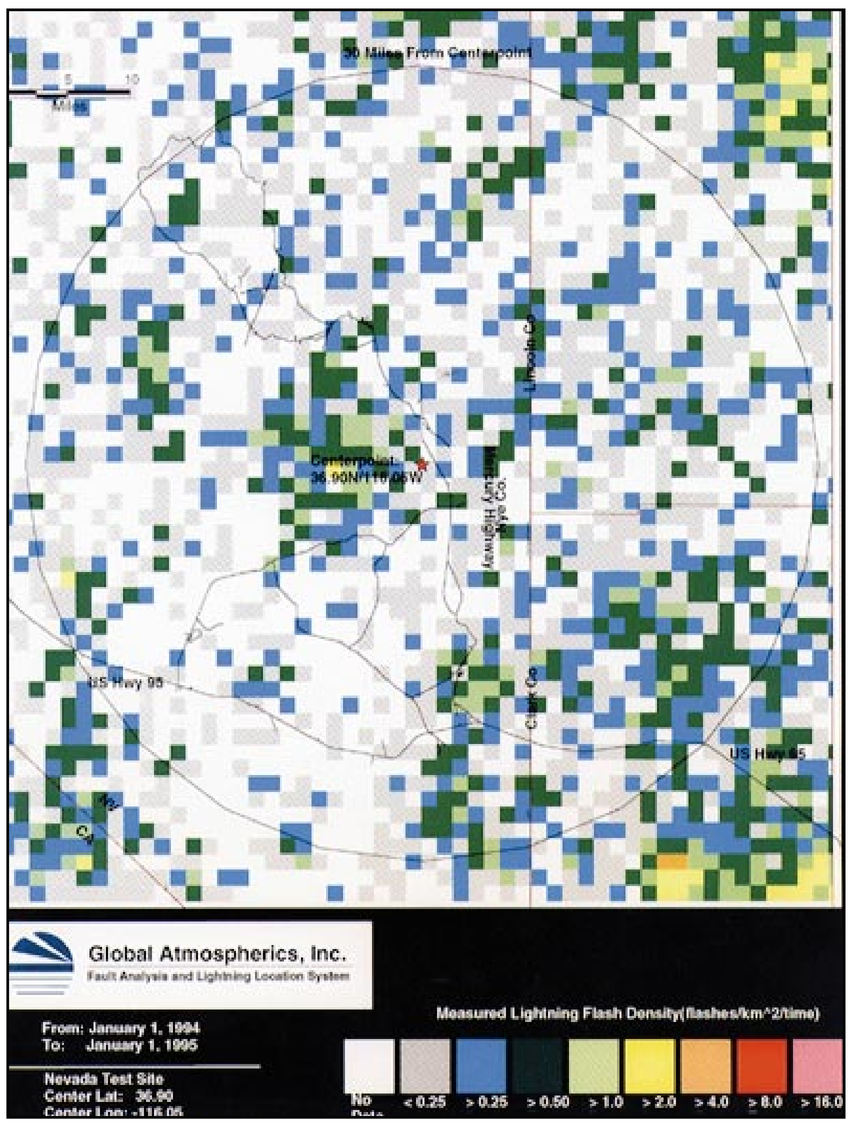
Ensuring that nuclear warheads and their components can withstand a lightning strike focuses on designing multiple physical barriers that block the transfer of energy from a lightning bolt to critical components and materials contained within a nuclear device. In addition, LLNL engineers use computer models to mimic the electromagnetic fields generated by lightning storms that can affect wiring connected to the high explosives found in every nuclear device. Other models, based on welding computer codes, simulate the effects of direct lightning strikes upon metal.

Another area of research is applying statistics to the threat of lightning to sharpen the estimates of the frequency of lightning strikes. The work is similar to Laboratory risk analyses regarding seismic safety and nuclear power plants.

When underground tests were being planned and conducted at the Nevada Test Site, Laboratory test personnel always kept a watchful eye on the weather. Instruments monitored atmospheric electrification, and the U.S. Weather Service operated a cloud-to-ground lightning locating system. During the late 1980s, the Laboratory Test Program adopted a lightning protection method designed by LLNL engineer Richard Hasbrouck that took advantage of the fact that the nuclear device system was contained within a steel enclosure. In Hasbrouck's design, called the Lightning-Invulnerable Device System, the explosive device and associated components reside within a "fortress," a closed, metallic surface connected to another grounded conductor similar to a Faraday cage. The design was validated through tests that first used simulated lightning at the Lightning Transient Research Institute in Miami Beach, Florida, and later rocket-triggered lightning at NASA's Rocket-Triggered Lightning Facility at the Kennedy Space Center.

The comprehensive lightning appraisal of the Device Assembly Facility at the Nevada Test Site discussed at the left was designed by Laboratory personnel. The appraisal identified weaknesses in the facility's lightning protection system through the use of a state-of-the-art swept-radio-frequency testing procedure.

Figure 2. One of several flash-density maps in the area of the Device Assembly Facility (DAF) at the Nevada Test Site in southern Nevada used to arrive at a strike probability estimate. The DAF is at the center of the map.



was originally designed to safely and securely house nuclear test device assembly activities and will be available to support DOE Defense Programs stockpile stewardship activities. Its roof, rear wall, and much of its side walls are earth-covered.

The concepts presented in the new guidance document were used to evaluate the DAF's lightning safety systems. In conducting the study, the review team focused on the main reinforced concrete structure, not the facility's peripheral outbuildings.

Traditional measurements showed that the DAF structure exhibited a low value of direct current resistance, not surprising because it contains a very large quantity of interconnected metal in good contact with the Earth. However, was it immune to lightning damage? To find out, the team went a step further and conducted an electromagnetic survey, consisting of low-level radio-frequency testing to determine lightning's likely penetration of the structure. (See the box on p. 11.)

The testing at DAF revealed that small to moderate amounts of lightning current could enter the interior via metallic paths provided by objects such as the vent stacks and antenna feedlines that penetrate the roof top. These findings are helping facility managers evaluate additional protective measures for the facility.

The study confirms that cloud-to-ground lightning represents a natural phenomena hazard in the DAF environment and estimates that lightning will strike some point of the facility about once every 20 years. This figure was arrived at by multiplying the ground-flash density at DAF, which is based on five years of actual NTS lightning strike data (Figure 2) and the lightning-attractive area of the DAF. If the DAF were entirely underground, its ground-surface area would be the lightning-attractive area. However, lightning-attractive area increases with object height. Consequently, the twelve 39-meter-tall metal light poles around the DAF's perimeter are most likely to be hit by large-to-severe amplitude strokes (greater than about 40 kiloamperes), while small-to-moderate ones are more likely to strike the structure.

An unexpected outcome of the analysis showed that a large peak-amplitude stroke to a light pole will produce essentially the same effects within the DAF structure as a small stroke attached directly to a point on

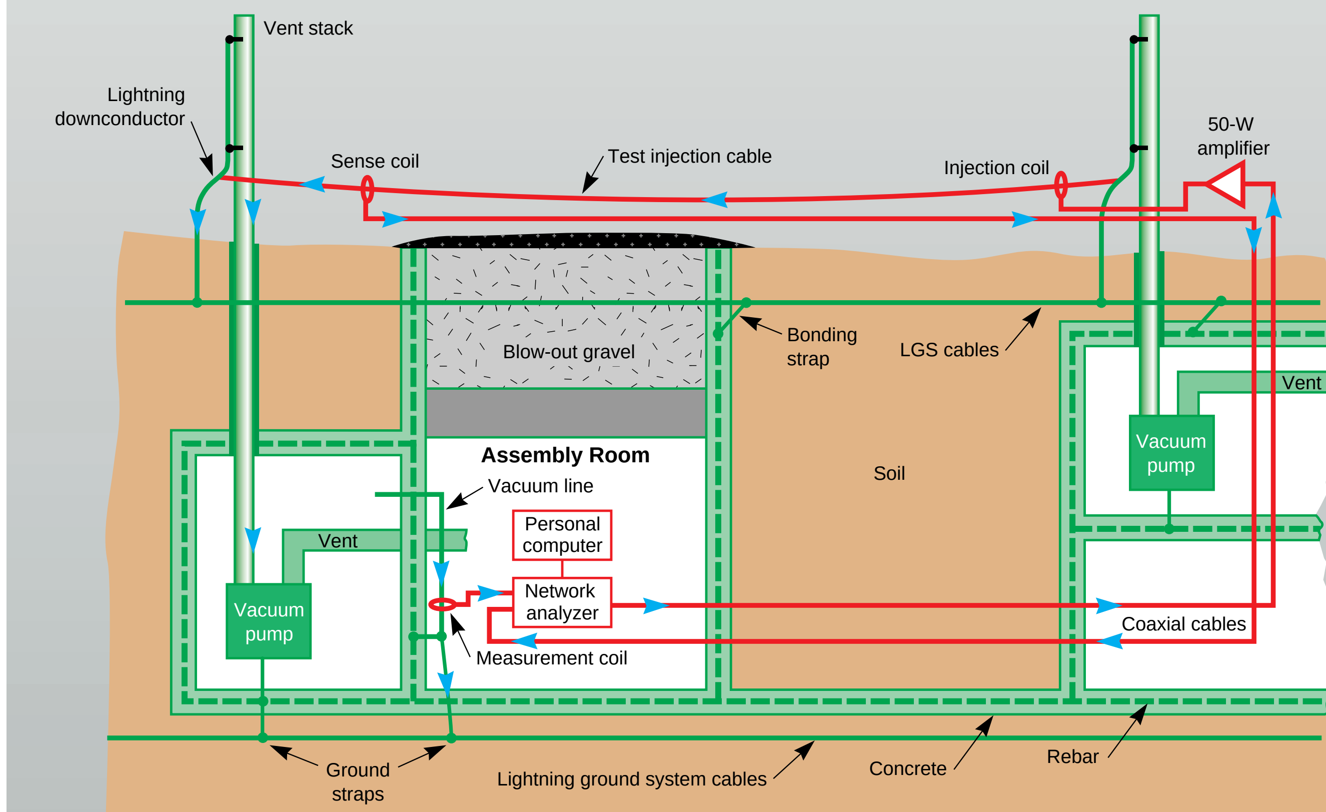
Low-Level radio-frequency testing at the Device Assembly Facility

Low-level radio-frequency (rf) testing was done on the Device Assembly Facility (DAF) at the Nevada Test Site to test the effectiveness of the DAF's lightning protection system. The block diagram below shows an assembly room at DAF outfitted with the rf testing system. The permanent DAF structural elements are in green; the testing system components are red.

During rf testing, the network analyzer continuously emits a signal over the range of 10 kHz to 30 MHz, representing (approximately) the rf spectrum of a lightning stroke. The analyzer's output signal travels through coaxial cable to the 50-watt amplifier located on the DAF's roof. The amplified signal then proceeds to an injection coil and through the test injection cable to lightning grounding system downconductors connected to two of the facility's metal vent stacks. These vent stacks are interconnected by means of the lightning grounding system's rooftop conductors. Such rooftop penetrations are unintentional electrical conductors, allowing lightning currents to enter the DAF. Various conductive paths inside the DAF, e.g., bonding and/or mechanical attachments, electrically connect the vent stacks to the DAF's steel rebar and the facility's lightning grounding system.

As the rf signal travels to the downconductor, it passes through a sense coil, which sends a sample of the applied signal back to the network analyzer. Because the injection cable will alter the rf signal, this sample provides the network analyzer with the characteristics of the signal being applied to the stack. The applied test signal will divide, with some portion flowing on the lightning grounding system conductors and some entering the DAF via the vent stack.

In the configuration shown, the testing system's measurement coil detects that portion of the applied signal flowing on the copper vacuum line and sends it to the network analyzer. The network analyzer compares this signal's characteristics to those of the applied signal sampled by the sense coil. The personal computer is used to analyze and archive the data. Later, this low-level data is scaled up to levels associated with a lightning strike, allowing modeling of worst-cast lightning effects on the facility to determine the adequacy of the facility's lightning protection system.



the structure's roof. The poles, therefore, are expected to effectively divert large-to-severe amplitude return strokes away from the numerous rooftop points of entry.

Hasbrouck is gratified that the DAF lightning study provided an opportunity to apply the concepts put forth in the guidance document. By employing radio-frequency penetration testing, it was possible to identify how and how much lightning energy would leak through "holes" in what the lightning protection code would have judged to be a solid facility. He notes that a 1993 lightning study of DOE's Pantex facility also recommended that some form of penetration radio-frequency testing be carried out in the future.

"Lightning knowledge," he emphasizes, "is neither archaic nor arcane. We cannot prevent lightning, but knowledge of it can help us enhance safety, protecting us and costly property against its damaging and potentially catastrophic effects."

Key Words: hazard management, lightning, radio-frequency testing.

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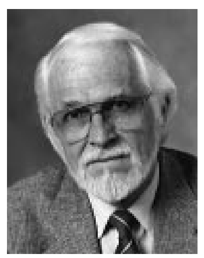
About the Engineer

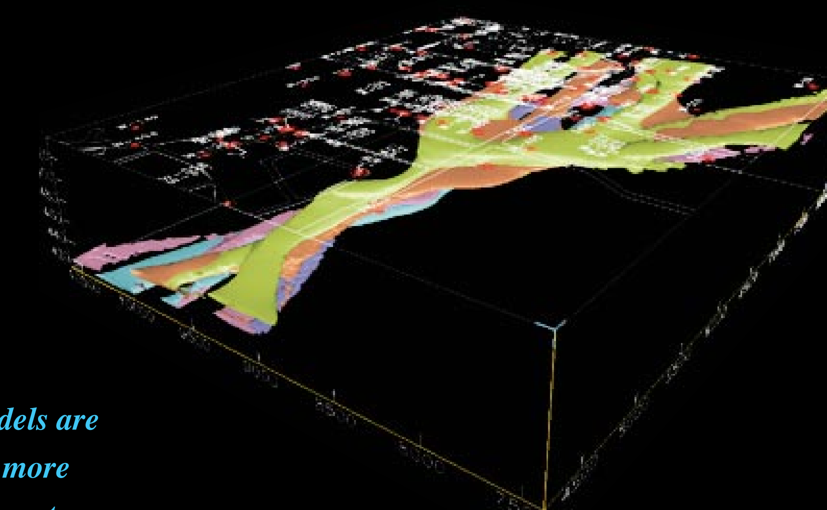


RICHARD HASBROUCK holds a B.S. in electrical engineering and is a Registered Professional Engineer in California. He joined the Laboratory in 1968 and is currently a senior electronics engineer. During his career at Lawrence Livermore, he has supported various projects in the test program. Involvement in nuclear explosive safety studies led to his study of lightning safety, culminating in the lightning hazard management concept. He has written numerous papers and reports on this subject and is co-author of the draft "Lightning Hazard Management Guide for DOE Facilities" (1995). Hasbrouck is a consultant and co-director for engineering of the National Lightning Safety Institute.

In a collateral Laboratory assignment, he is the aviation project officer responsible for the aviation safety interface between Lawrence Livermore and the DOE on Laboratory projects related to aviation, and he was general manager of the Laboratory's F-27F aircraft operation. Prior to joining the Laboratory, he designed, tested, and fielded electro-optical, instrument servomechanisms for astronaut training simulators produced by Farrand Optical Co. in New York for NASA's Project Apollo.

Groundwater Modeling: More Cost-Effective Cleanup by Design

Computer modeling is proving its usefulness as cleanup of contaminated groundwater proceeds at the Livermore site. Modeling is an extremely effective tool for deciding where and how groundwater remediation efforts should be directed. Our models are being made available to others for more efficient remediation around the country.



GROUNDWATER modeling uses mathematical methods to help scientists "see" what is happening underground, to make up for what we cannot see with our own eyes. The discipline of groundwater modeling has been around for at least 25 years, but with the powerful desktop computers and advanced software available today, computational modeling is an easier and more effective task than it used to be. Evaluation processes that used to take days or even many weeks can now be done in minutes and often with a higher degree of accuracy.

We have developed several new software tools that can be used by groundwater remediation planners anywhere. MapIt, for example, can read a variety of one-, two-, and three-dimensional data sources and will allow remediation planners to rapidly produce input files for the various simulation codes. With MapIt, we have reduced the time needed to regrid and execute new three-dimensional conceptualizations from months to hours. In the past, a different "code preparation" program was required for each groundwater simulation code. Another tool is PLANET, an easy-to-use, point-and-click, drag-and-drop program that replaces laborious, manual operation of modeling codes to evaluate alternative remediation scenarios (Figure 1). Using these and other newly developed tools, groundwater scientists or engineers at Lawrence Livermore National Laboratory and elsewhere can quickly prepare and simulate robust three-dimensional conceptual models of our site.

We now have the ability to simulate groundwater flow and transport in a large number of possible configurations