LIGHTNING SAFETY AND LARGE STADIUMS

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Many stadium managers do little to anticipate or control the threat of lightning when large crowds gather.

We attended a University of Colorado football game at Denver's Invesco Field on Saturday, 20 August 2003. For this highly contentious game between intrastate rivals Colorado State and the University of Colorado, Invesco Field provided a neutral site and the capacity to accommodate large crowds. The official stadium attendance for that night was 76,219 people.

During the third quarter, lightning lit up the southern sky as heavy rains blanketed the stadium. A public address announcement stated that the game was suspended due to lightning, ▶

A lightning strike was photographed near Virginia Tech's Lane Stadium. See figure 2 on page 1192 for more details.

and all players, coaches, and stadium personnel on the field immediately ran for cover. During the 30–45-minute delay, stadium management did not provide any instructions to spectators. Many crowded the exit ramps and concourses to escape the downpour, while others remained in their seats during the storm. The game eventually resumed with no reported injuries to players or spectators resulting from the storm. Yet, we wondered why the event managers gave no direction to protect the 76,219 spectators from the dangers of lightning.

A review of lightning casualty cases identified a woman who was struck as an off-field spectator at a concert held in Washington, D.C.'s, Robert F. Kennedy (RFK) stadium on 6 June 1998 (Milzman et al. 1999). Stadium officials evacuated more than 50,000 spectators shortly after that strike. This event demonstrates the reality that lightning can strike and injure spectators in outdoor stadiums. Furthermore, experiences at Invesco Field and RFK stadium reveal a lack of consensus and expertise when dealing with lightning safety procedures for large numbers of spectators.

Large outdoor stadiums face a significant vulnerability to lightning. To date, there have been few casualties in the United States from direct lightning strikes to a stadium or from the mass movement of spectators when lightning threatens. However, if stadium managers do not develop action plans for lightning safety, venues are overlooking an opportunity to prevent a potential disaster while the costs of intervention remain substantially low.

Given that real-time lightning monitoring systems are widely available and there is general agreement concerning locations and procedures that substantially reduce the lightning threat, stadium managers can take proactive steps to mitigate the risks posed by lightning rather than embrace the false assumption that no specific lightning policy can anticipate/control the threat. In this article we will do our best to connect what is known about existing lightning protection technology and crowd management strategies to recommend guidelines for the enhanced safety of the large number of spectators that attend events in outdoor stadiums. Numerous other weather events could pose a hazard to stadium occupants (for more about the close call of a 2005 tornado threatening an Iowa State football game, see the sidebar on pages 4 and 5), and we recommend that stadium managers consider the risk of tornadoes and hail in addition to the threat of lightning covered in this article.

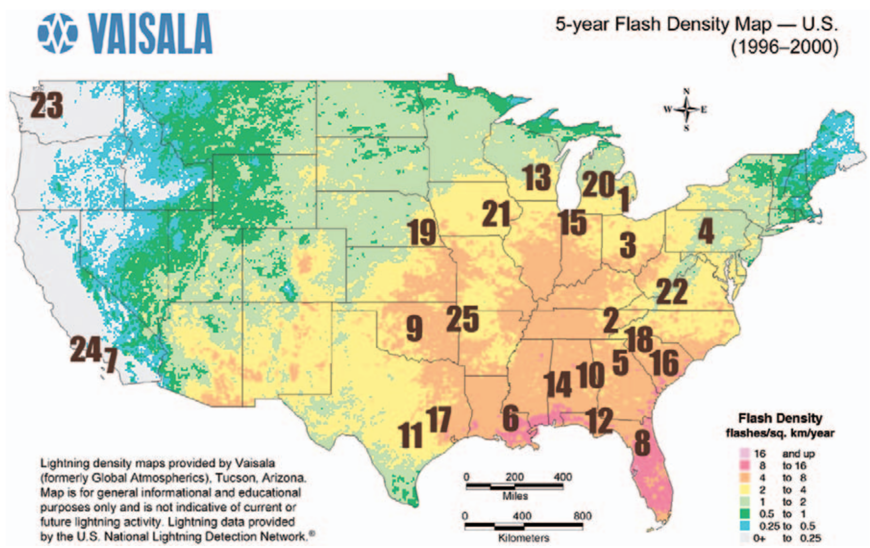

Fig. 1. Average density of lightning strikes over 5 years. Strike density is measured in strikes per square kilometer per year. Black numbers (1–25) denote the 25 largest National Collegiate Athletic Association (NCAA) Division I football stadiums based on average per game attendance for the 2005 season. Table 1 provides more information on each school. Although the base map is made from older data, these were the best-calibrated data available at the time of publication (base map courtesy of Vaisala 2005).

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IS LIGHTNING A DANGER TO STADIUMS? Because college football has many of the largest stadiums in the United States, Fig. 1 uses these stadiums to visualize the lightning threat to large outdoor stadiums in general. This graphic depicts the location of the top 25 stadiums with the highest average attendance on a base map of average annual lightning strikes during the 5-year period from 1996 to 2000. Each stadium is described further in Table 1. The area of the greatest lightning frequency is generally collocated with the largest collegiate stadiums across the central and southern sections of the United States. Although the statistical threat of a lightning strike (cf. Krider and Kehoe 2004) within a stadium is very low, Fig. 1 should at least serve as a qualitative warning to stadium managers that large outdoor events often occur in the areas of the most frequent lightning strikes.

In addition to the theoretical warning to stadium managers in Fig. 1, an empirical warning also exists. Just in the past few years, lightning impacted the college football games listed in Table 2, with a combined attendance of over 500,000 fans. Thus, the lightning threat is both theoretical and real, and should not be pushed aside.

Although large stadiums pose safety challenges due to their size, crowd density rather than crowd size is the overwhelming concern in lightning safety policies. If a stadium is relatively empty, it is easier for spectators to move quickly to shelter. But, in the case of the seven events listed in Table 2, the stadiums were filled near to or over capacity resulting in a situation where mass crowd movement is difficult and even dangerous. In fact, the National Fire Protection Association's guidelines for lightning protection lists the "risk of pannic . . . " as the number one safety concern for large venues

Table 1. The 25 largest NCAA Division I football stadiums by average game attendance for the 2005 season.

Rank	School	Average attendance per game
1	University of Michigan	110,915
2	University of Tennessee	107,593
3	Ohio State University	105,017
4	The Pennsylvania State University	104,859
5	University of Georgia	92,701
6	Louisiana State University	91,580
7	University of Southern California	90,612
8	University of Florida	90,406
9	University of Oklahoma	84,331
10	Auburn University	84,161
11	University of Texas	83,333
12	Florida State University	82,724
13	University of Wisconsin	82,551
14	University of Alabama	81,018
15	University of Notre Dame	80,795
16	University of South Carolina	79,867
17	Texas A&M University	79,732
18	Clemson University	78,417
19	University of Nebraska	77,485
20	Michigan State University	75,183
21	University of Iowa	70,585
22	Virginia Tech	65,115
23	University of Washington	64,326
24	University of California, Los Angeles	64,218
25	University of Arkansas	63,678

Table 2. Recent Division I college football games that were delayed by lightning. Numerous other events in outdoor stadiums were delayed by lightning and this list should only be considered an example of the true impact of lightning on large stadiums.

Date	Location	Attendance	Percent of capacity
18 Sep 2004	University of Arizona	50,111	86.7%
4 Sep 2004	Louisiana State University	91,209	99.6%
27 Sep 2003	University of Alabama	83,189	99.3%
14 Sep 2002	University of Florida	85,185	102.6%
14 Sep 2002	University of South Carolina	82,138	102.4%
14 Sep 2002	University of Oklahoma	75,104	103.2%
1 Aug 2000	Virginia Tech	56,272	112.5%

(NFPA 2004). Therefore, stadium managers should acknowledge not just the physical threat of a direct lightning strike, but also the crowd management issues of trampling and bottlenecks in crowd flow that could pose a greater threat to spectator safety.

In addition, because spectators will still attend an event with thunderstorms in the forecast, event managers should take on the responsibility for ensuring spectator safety because most spectators enter the stadium and surrender any access to real-time warnings of thunderstorms [with the exception of the minority of spectators with wireless weather access via a cell phone/personal digital assistant (PDA)]. Although some fans might use radios that provide commentary on the game and may also provide weather warnings, the usual audible and visual clues that most people rely upon to assess the lightning threat may be obscured by crowd noise or impeded by the stadium structure and the stadium lighting. Therefore, it is the responsibility of stadium management to monitor any lightning activity and have an appropriate action plan in place.

CURRENT LIGHTNING PROTECTION STRATEGIES. Guidelines do exist that can aid stadium managers to establish an effective lightning action plan, but sometimes officials do not develop plans until after an incident occurs. During a football game on 27 August 2000, a thunderstorm produced 12 lightning strikes within one mile of the center of Virginia Polytechnic Institute and State University's (Virginia Tech's) Lane Stadium, with

"CYCLONE" THREATENS CYCLONE GAME

—William A. Gallus Jr.
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The last home football game each November at Iowa State University (ISU) is usually a time where fans and officials alike worry about snow and cold. On 12 November 2005, however, the 50,000 fans arriving in balmy conditions to watch the Cyclones play the University of Colorado Buffaloes were likely happy to trade wintry fears for the tornado watch that had been issued at 1400 LST, 4 hours before kickoff. Not so for emergency management officials, who had known about a severe weather threat for days in advance. An emergency meeting was called at 0900 LST the morning of the game, with representatives from the city of Ames' hospital, police and fire departments, and the university present. A critical incident plan was reviewed at that time, with some adjustments made in anticipation of possible weather problems toward game time. For instance, several large buildings within roughly half a mile of the stadium, often locked on weekends, were opened to be used as potential shelters. Officials also printed up 6,000 flyers, explaining the heightened risk of severe weather, to be distributed to arriving fans and read from police car bullhorns to the crowds tailgating that afternoon. The flyers mentioned what to do in the event of two different severe weather scenarios—one involving lightning and hail, and the other tornadoes.

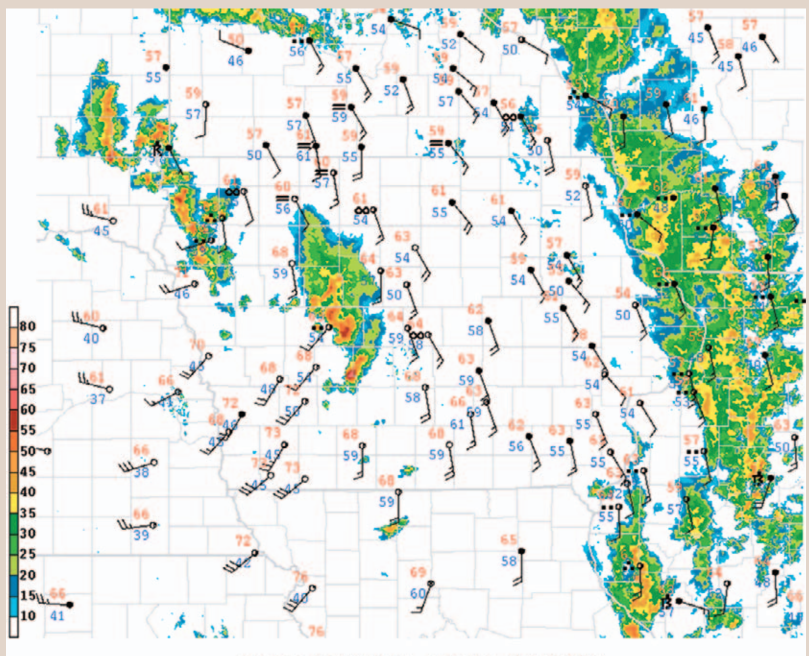

Fig. S1. IEM plot of surface observations with radar reflectivity overlaid valid at 1600 LST on 12 Nov 2005.

Supercell thunderstorms developed in western Iowa before 1500 LST and began producing rapidly moving tornadoes by 1630 LST. The Iowa Environmental Mesonet (IEM), a partnership between the National Weather Service (NWS), ISU, KCCI-TV in Des Moines, and the Iowa Department of Transportation, was instrumental in conveying the danger of the approaching storms, not only because of its relatively dense network of surface stations [covering the state at approximately one station per 40 km (1600 km^2) cell with highest density in central Iowa] but also its remotely controlled webcams (there are now 20 statewide). An Iowa Environmental Mesonet (IEM) surface plot valid at 1600 LST (Fig. S1) showed one of the initial strikes occurring only 0.6 miles away during the opening kickoff (Fig. 2). Although there were no reports of lightning directly striking the stadium, there were significant problems with controlling the crowd that filled Lane Stadium to over 100% capacity. A lack of a defined plan to handle such a situation led to confusion and an ineffective response from stadium management, but Virginia Tech has since developed an action plan specific to lightning that includes instructions for stadium management, police, ushers, players, and spectators.

In other cases, stadiums are proactive in the development of a lightning safety plan. The University of Tennessee's lightning action plan includes both monitoring procedures for lightning and evacuation directions that stadium personnel communicate to the fans. When lightning is within 10 miles of the stadium, the University of Tennessee plan calls for people to clear the field and addresses the exact egress routes for spectators.

The partial or full evacuation of a stadium may be an effective lightning safety plan for spectators, but stadium managers should recognize that mass crowd movements pose additional and serious challenges to the safety of a crowd. The study of crowd dynamics uses computer modeling and can provide reasonable assumptions of crowd egress time, load points where the crowd flow may encounter problems (e.g., a single escalator/turnstile), and how many people can fit in a specified area that may serve as an effective lightning shelter. For example, if people move to a safe location

Fig. S2. IEM web camera view of Woodward, Iowa, tornado, looking west-southwest from Madrid, Iowa.

Fig. S3. IEM web camera view of Ames tornado from Iowa State University, looking northwest.

intense storms in west-central Iowa moving into a region with enhanced tornado potential due to southeasterly surface winds.

Athletic department officials maintained close contact with the Des Moines NWS office during this time, as over 50,000 fans tailgated outside the stadium. A particular concern on this afternoon was the forecasted 50–60 m.p.h. north-northeast movement of the storms, which could shorten warning time. Based on the storm upstream, officials opened gates into the stadium 10 minutes early, at 1620 LST, believing fans would be more sheltered in the stadium than stranded outside. At 1639 LST, an F2 tornado from this storm could be seen live via the IEM Madrid webcam (Fig. S2) causing damage in the town of Woodward, roughly 15 miles southwest of the stadium. Some fans tailgating in the stadium parking lots watched this tornado on their portable televisions.

Based on the approaching storm, at 1645 LST officials ordered an evacuation of the stadium based on a scenario 1 event, urging people to seek shelter in their cars to avoid lightning and hail. At this same time, a tornado was reported 8 miles southwest of the stadium. That information resulted in a scenario 2 evacuation being ordered by 1650 LST, and fans instead were told to seek shelter in large buildings, most a 5–10-minute brisk walk away, stadium concourses, restrooms, and ditches. Figure S3 shows the IEM webcam at 1701 LST from the ISU campus, one mile from the stadium, as a tornado caused F2 damage 3 miles NW of the stadium. Over 10,000 people took shelter in the university's Hilton Coliseum, with several thousand more walking to other buildings. Even larger numbers, however, remained outside and unsheltered. Like many colleges, ISU's stadium is off campus, surrounded by fields with limited possibilities for sheltering fans. A tragedy was avoided by 3 miles in this event, and in the end, the "cyclone" only delayed the Cyclone game by 40 minutes.

Fig. 2. Looking west-northwest from Virginia Tech's Lane Stadium as lightning strikes at a distance of 0.6 miles (1 km). The strike occurred at 8:50 p.m. on 27 Aug 2000, moments before the opening kickoff (courtesy of the Roanoke Times 2000).

and have equal to or less than 3 ft^2 per person to stand, involuntary touching and brushing against others will start to occur (Fruin 1984). Using this threshold, managers could calculate the available square footage of the stadium that would be considered a safe shelter from lightning and would provide a reasonable amount of personal space for inhabitants. The field of modeling crowd dynamics with computers is relatively young, but there are increasing applications of this research (Bohannon 2005), with one important possibility focusing on the evacuation of stadiums in emergency situations.

In addition to or in place of any stadium evacuation, another option exists to complete lightning protection systems that would guard all seating areas. This type of in situ protection uses air terminals (lightning rods) and caternaries (shield wires) to transmit the lightning that strikes the stadium safely to the ground and away from stadium electronics, plumbing, and people. Architects and engineers design air terminals and caternaries to protect structures but do not always design these features to protect all of the seating areas in stadiums. For a few tens of thousands of dollars (C. Andrews 2003, personal communication), stadiums could add to their existing lightning protection systems to ensure protection of all seating areas (Fig. 3). If properly installed, wires that suspend television cameras over the stadium could also act as caternaries. And these types of lightning protection can be rather unobtrusive for the spectators, because air terminals could be disguised as flagpoles and caternaries would hardly impede any sight lines in the stadium.

By protecting most or the entire stadium seating area, a full or even partial evacuation would be unnecessary. In effect, players would clear the field but spectators could move freely and without panic because they would be protected from the lightning in any part of the stadium. Numerous sources discuss the design and effectiveness of air terminals and caternaries (Moore et al. 2003, 2000; NFPA 2004). Further, stadiums should be wary of implementing new lightning protection technology that employs devices to "prevent" lightning from occurring or from striking a structure, because there is no empirical proof in the literature that these systems work as advertised (Uman and Rakov 2002).

SUGGESTED ASPECTS OF A LIGHTNING ACTION PLAN. Following is a brief review of existing lightning safety guidelines for large groups and the important components of an action plan (Holle et al. 1999; Zimmermann et al. 2002). For more information on tips to stay safe from lightning, please visit this comprehensive source online at: www.lightningsafety.noaa.gov:

- Stadiums should designate a responsible person(s) to monitor the weather and initiate action when appropriate. Monitoring should begin hours and even days ahead of an event. Computer-based lightning monitoring is suggested for large venues because crowd noise and lighting make visual and audible lightning observation difficult.
- A protocol needs to be in place to notify all persons at risk from the lightning threat.
- Safer sites must be identified beforehand, along with a means to route the people to those locations.
- The all-clear signal must be identified and should be considerably different from the warning signal. The signal should be sounded 30 minutes after the last sound of thunder. Clearing skies and an end to the rain do not guarantee that the lightning threat is over.

- Lightning safety tips and/or the action plan should be placed on game programs, flyers, the large television screen at stadiums, and on placards around the area. Lightning warning signs are an effective means of communicating the lightning threat to the general public and raising awareness (Bennett et al. 1997).

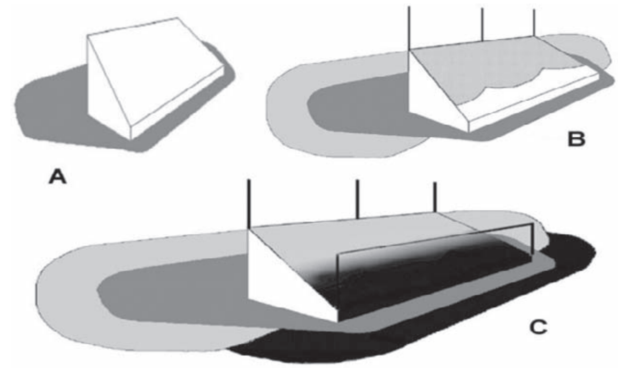

Fig. 3. Various zones of protection from lightning. (a) Zone of protection (dark gray) created by standalone seating. (b) Augmented zone of protection (light gray) created by fitting the existing seating area with three air terminals (lightning rods). (c) Additional zone of protection (black) created by hanging a caternary (shield wire) across the front of the seating area.

CONCLUSIONS. Stadium managers should develop an action plan to deal with lightning because there is sufficient knowledge of crowd management techniques and lightning protection devices to enable an effective proactive response. Part of this action plan may call for targeted evacuations of at-risk parts of the stadium (including the playing field) and/or enhanced coverage of air terminals and caternaries to protect all spectator areas. Although the details of an action plan may differ, the constants in any action plan involve education of stadium personnel, players, and spectators with significant and recognizable visual and audible communication. Also, stadiums must employ a strategy to monitor for lightning, which could involve contracting with a private weather service provider, installing in-house lightning equipment, or a combination of both.

A typical lightning action plan should involve the following components:

1) Assess the stadium's current protection from and vulnerability to lightning. Identify areas of the stadium that could be considered safe from lightning and how many people would need to move to these safe areas from other unprotected areas. Contact stadium architects/engineers/lightning safety experts for help in this area.
2) Consider the feasibility of moving/evacuating people in unprotected areas to safe areas and whether these safe areas are all within the stadium or include external buildings. Determine the necessary time to move these people to safety, and recognize that these people should be in safe areas by the time lightning is no closer than 6 miles away (which equates to approximately 30 seconds between seeing the lightning flash and hearing the thunder). Contact stadium architects/engineers/crowd modeling experts for help in this area.
3) Decide if evacuation is a possible solution because the great lead time needed for an evacuation will likely result in many false alarms where lightning does not present a close threat to the stadium. Numerous false alarms will eventually create an apathetic crowd and could put added pressure on stadium management to continue games in the face of large contracts for television coverage and event endorsements.
4) If evacuation seems impractical, consider added lightning protection devices such as more air terminals and/or caternaries to protect spectators in most/all seating and community areas. Contact stadium architects/engineers/lightning safety experts for help in this area.
5) Develop a holistic plan to implement action based on the "Current lightning prediction strategies" and "Suggested aspects of a lightning action plan" sections, also including the following:

   - Enact a lightning monitoring program with a lead person in charge of maintaining contact with a private weather services company and/or monitoring in-house lightning detection software.
   - Develop a chain of command between the lead lightning monitoring person and other stadium officials and event officials and a timeline for decision making about the situation.
   - Based upon the solution obtained in above-mentioned sections and the chain of command, clearly delineate procedures for stadium personnel, players, and spectators to maintain crowd order and reduce the possibility of panic. These procedures should also include instructions for when to resume the event (30 minutes after the last thunder is heard).
   - Post the procedures on tickets, flyers, large stadium television screens, and placards lo-

cated around the stadium, and announce a summary of these procedures at each event because constant education is an effective tool to raise awareness.
- Make certain that auxiliary plans are in place to handle worst-case situations where the stadium may lose audible communication, power failures, etc.

Although lightning is still not well understood and occasional "bolts from the blue" do strike far away from any significant weather (Hodanish et al. 2004), stadium managers should develop and implement a lightning action plan to deal with the real but addressable threat of lightning.

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