3.3 DEVELOPMENT OF OPTIMAL LIGHTNING WARNING PROCEDURES USING PROBABILISTIC RISK ANALYSIS

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1. INTRODUCTION

Modern Lightning Detection and Warning Systems (LDWSs) provide the technology needed to support prompt and effective alerts for the protection of personnel and facilities. In practice, the effectiveness of such alerts depends critically on the actual procedures used to curtail operations, effect evacuation to safe locations, and allow for the resumption of activities after lightning is no longer in the area. In this paper, we show how probabilistic risk assessment (PRA) can be used to develop lightning hazard control procedures to obtain an optimal risk/cost ratio. The metric used here for cost is the time period for evacuation, which is a rough substitute for a more detailed analysis that takes into account the various monetary impacts of interruptions in operations and reflects the fact that the capital and operating costs associated with an LDWS are typically only a small fraction of the indirect costs associated with evacuations. The approach uses Monte Carlo (MC) simulation to model the random behavior of storms at a particular location. The model also considers existing or proposed procedures used to declare warning, alert, and all-clear conditions. Variations in risk and the time associated with personnel sheltering are calculated as direct outputs of the analysis.

The original motivation for this analysis was to characterize the lightning risk associated with outdoor high-explosives (HE) operations at an experimental facility at Los Alamos National Laboratory (LANL) in northern New Mexico (Eisenhawer, 2002). The Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility is a very large flash x-ray machine used to study the behavior of materials at high strain rates. Lightning-induced accidents involving high-explosive violent reactions (HEVRs) are a significant concern at DARHT. If an HEVR were to occur while personnel are at the firing site, fatalities would be very likely.

To address this risk, an LDWS was installed and a set of lightning hazard control procedures to define how warning, alert, and all-clear states were implemented. We refer to the LDWS and associated procedures as the lightning risk management system (LRMS). The LDWS became operational in the summer of 2001 and the LRMS was implemented. No attempt was made a priori to quantify the anticipated risk reduction resulting from the use of the LRMS, nor was the expected cost associated with the time spent on lightning alert (when experimental activities cease) analyzed. Operation, albeit with the usual start-up problems, was judged successful; however, it was apparent that the costs associated with lightning-induced delays in operations were significant. To determine whether the risk/cost ratio was appropriate, a quantitative review of the risk reduction provided by the LRMS and the potential for more efficient implementation of the procedures was performed.

Probabilistic risk is a well-established and powerful tool for evaluating the safety of processes or systems when uncertainty is significant (Thomson, 1987). Risk is defined as the *expected loss*. Here the loss is composed of possible casualty consequences (that is, injuries and deaths and economic consequences arising from the loss of experiments, etc.) The term *expected* is understood to represent the process of accounting for the fact that a set of conditions may not necessarily always lead to consequences and that there is a possible range of consequences given nominally identical conditions. Therefore, risk includes uncertainty as a fundamental aspect. This uncertainty may arise from the stochastic nature of physical processes or arise from imperfect knowledge. Thunderstorms, the associated lightning, and the response of HE to lightning all exhibit uncertain behavior, and therefore, the risk is a valuable metric for measuring safety. In PRA, uncertainty is expressed using probability density functions (PDFs) for the major parameters that determine the behavior of the process or system under analysis. In this case, *expected* is understood to represent the mean value determined from the risk PDF. In this analysis, PRA is applied to the process of working with HE with the potential for lightning hazard conditions, and the expected number of fatalities is estimated. When many random variables are combined to estimate a metric, as is the case here for risk, MC simulation may be used to estimate its PDF (Kalos, 1986). Many individual simulations of the stochastic process are performed, with the input values of random variables chosen by "rolling the dice." Each simulation in our case represents a separate estimate for the risk.

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2. LIGHTNING RISK MANAGEMENT SYSTEM

The LANL LRMS used at DARHT includes the LDWS, which provides time-dependent lightning information, and the risk management procedures, which govern the actions to be taken when lightning occurs in the vicinity. The LDWS used at LANL is a Precision Lightning Warning System from Vaisala-GAI of Tucson, Arizona. The system, as originally configured, consisted of a satellite link to the National Lightning Detection Network (NLDN) and two electric field mills (EFMs) with a network link to a central alarm workstation located at the Access Control facility for HE operations. One of the original EFMs is located on top of a building approximately 1 km from DARHT. The second is located at a separate experimental facility approximately 8 km southeast of DARHT. Additional EFMs have been added to provide increased lightning protection at several other facilities located many kilometers from DARHT. The number of EFMs currently installed is six (summer 2004). The LDWS system and the initial operating experience are discussed in Odom (2002).

The use of the LDWS in HE operations is defined in a set of control procedures for the DARHT facility. There are three operational states: all clear, watch, and alert. The all-clear state is in effect if there have been no alert and no watch events for 30 min. An alert is declared if either of the EFMs exceeds 2 kV/m[*] or there is a detected cloud-to-ground (CG) flash within 10 km of DARHT. When an alert is declared, the firing site must be evacuated promptly and personnel must take cover inside DARHT. An exit from the alert condition occurs when there is no alert event and no watch event within 30 min. The watch state is entered if the gradient is between 1.5 and 2.0 kV/m or there is a flash between 10 and 16.1 km of DARHT.[†] During a watch state, increased vigilance for lightning is to be in effect, and operations are to reflect the fact that an alert may be imminent. An exit from a watch state occurs if there is a transition to an alert or there is no watch event in 30 min. Note that an alert is declared if there is a flash within 10 km of DARHT but that the return to all-clear status does not occur until there has been no flash within 16.1 km for 30 min. We consider the effect of this control in the following section. In this paper, we discuss mainly the NLDN component of the LDWS and the associated procedures. We discuss the EFM component of the LDWS in a companion paper presented at this conference.

[*] The electric field control thresholds are mandated for outdoor HE operations (DOE, 1988).

[†] The actual distances in the procedures are stated in Imperial units, 6 and 10 miles, respectively.

3. MODELING THE RANDOM BEHAVIOR OF LIGHTNING STORMS

The Lightning Risk Model (RM) is required to reproduce the time and spatial distribution of lightning strikes around DARHT, provide flexible modeling of lightning risk management procedures, and capture the range of consequences resulting from a lightning strike. The first of these requirements is met by basing the flash time-position model (FTPM) portion of the RM on a careful analysis of local NLDN data, supplemented where necessary by more generic data from the literature. A short description of the environs of the facility and its weather patterns sets the stage for a discussion of the RM.

DARHT is located in Los Alamos county, New Mexico, on the Pajarito Plateau, at an elevation of 2190 m. This location is at the base of the Sierra de Valles mountains, the remnants of the Jemez volcano. The two closest mountains are Cerro Grande [elevation 3097 m] and Pajarito Mountain [3182 m]; both are approximately 12 km away and form the Eastern rim of the Valles Grande caldera. The lower edge of the plateau is approximately 10 km to the east [elevation 1950 m], where it meets the Rio Grande River. Approximately 25 km farther to the east are the Sangre de Cristo Mountains. A large fraction of the lightning storms in this region occur during the summer months as a result of the southwest monsoon, typically beginning about July 1. Localized convection cells develop on the upslope of the Sierra de Los Valles and move to the east over the Plateau. Thunderstorm activity is also prevalent in the Valle Grande, along the Rio Grande, and on the western slopes of the Sangre de Cristos. In the summer, lightning activity in these regions is essentially independent from the area of interest on the Pajarito Plateau. The proximity of DARHT to the Sierra de Valles mountains and the presence of localized storms within 20–30 km that rarely approach the facility strongly influence lightning risk and the effectiveness of the LRMS in reducing risk.

Lightning exposure commonly is expressed in terms of flash-rate density—flashes per unit area per unit time. CG flashes are detected by the NLDN (Cummins, 1998). The NLDN uses time of arrival and magnetic direction-finding data from a collection of more than 100 sensors to provide timing, location, and multiplicity information for flashes detected in the contiguous United States. NLDN data for the years 1994 to 1999 and 2001 were provided to LANL by Global Atmospherics (now Vaisala-GAI), operator of the NLDN. At the time the data were collected, the NLDN had a flash-detection efficiency of 0.8 to 0.9, depending on the peak flash current and location with a nominal location accuracy of 0.5 km. The average flash density in an area with a radius of 10 km centered about DARHT is 0.0097 F/km^2/D (0.04 F/mi^2/D), or an annual rate of about 3.5 flashes per square kilometer. The 10-km radius corresponds to the alert circle defined for the LDWS. Flash-rate density varies from year to year and according to the season. In Los Alamos, most of the flashes occur in July and August, corresponding to the monsoon season as noted above. The mean numbers of flashes in the alert area are 327 and 332 for July and August, respectively. The number of flashes varies more in July than in August, with a standard deviation of 197 vs 141. This phenomenon is explained by the variation in the onset of the monsoonal weather pattern and correlates well with precipitation records for these months (Watson, 1993).

The basic structure of the FTPM is shown in Fig. 1. We define a central area as the "storm cell."[†] Most of the CG flashes occur within a generally circular area with a radius R_s, 2 <= R_s <= 10 km. This radius was determined using the space-time correlation method of Finke (1999) to estimate the CG circular footprint (as well as the velocity) of strong storms in the vicinity of DARHT.[‡] Flashes also occur outside of this area, but with rapidly decreasing frequency as the distance from the cell center increases. This storm structure persists through virtually the entire electrically active part of the storm, independent of cell movement. The flashes have a uniform angular probability density function relative to the cell center and an inverse radial probability density function about the cell center. A cell moves with an identifiable velocity and, it is assumed, without significant shape or scale changes. A storm is represented by a moving circular cell. The ground position distribution of CG strikes is based on the instantaneous position of the cell center. The site of interest (in our case, the explosive firing site at DARHT) is at the center of another (stationary in this case) circular region, referred to as the accumulation area.

[†] The actual convective cell in the atmosphere that is the source for the CG lightning is smaller. The size of the storm to an observer on the ground appears to be larger.

[‡] The details for many of the analyses discussed in this paper, as well as a more extensive discussion of the results, are described in Bott and Eisenhawer, 2004.

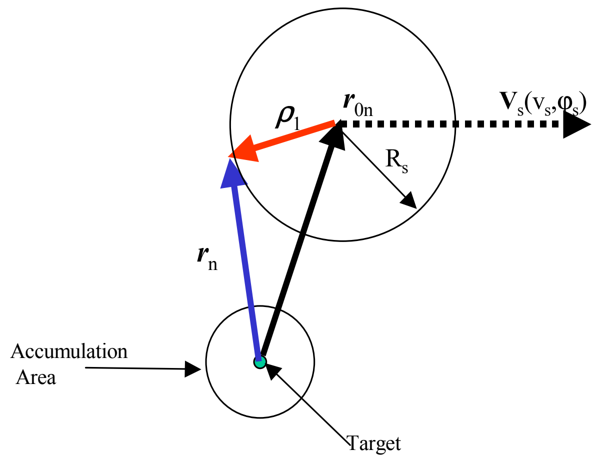

Fig. 1. Basic flash time-position model.

By using this model in an MC simulation, we can calculate the probability that a target area will be struck during the course of a time period τ. A storm cell normally is not stationary relative to the ground. The observed motion of local storms may be captured by shifting the center of flash activity and thus the distribution of successive flash positions, as well. We assume that this movement is represented by a constant velocity vector.[**] The random variable v_s describes storm speed and the random variable φ the direction of the velocity vector. During the time dt_n between flashes n-1 and n, the storm center moves to a new position that differs from its previous position by

$$\Delta\rho_{sc} = v_s e^{i\varphi}\left(t_n - t_{n-1}\right) = v_s e^{i\varphi} dt_n \quad . \tag{1}$$

In this model, the CG strike density is uniform within the cell. The radial distribution of strikes outside the cell, in the penumbra, is modeled using a Pareto distribution (Christensen, 1984). The Pareto distribution was chosen because of its shape, shown by the dark blue lines in Fig. 2. The spatial parameter of the Pareto distribution is the cell radius. Based on literature describing "blue sky" strikes, the shape parameter is chosen such that the probability of a penumbra flash beyond 19.4 km (12 mi) from the cell edge is 0.1.[††]

[**] The simulation can handle time-varying storm velocity vectors equally well if the supporting data can be obtained.

[††] Approximately half of all lightning flashes have multiple strokes, with ground terminal points that are separated spatially from the initial stroke (Thottappillil, 1992). In addition to the "direct" strikes described above, these "secondary" strikes arising from secondary strokes are included in the FTPM.

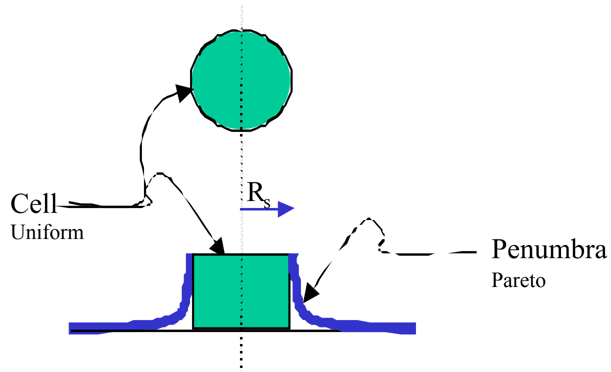

Fig. 2. Flash radial distance model.

Using the described model, the position of the n^{th} flash in the absence of storm movement is

$$\vec{r}_n = \vec{r}_{0n} + \rho_n e^{i\theta_n} , \tag{2}$$

where ν, φ, and dt_n are all random variables with probability distributions based on local NLDN data. The general expression for the position of the n^{st} flash, taking into account the cell motion, is then

$$\vec{r}_n = \vec{r}_{0n} + \rho_n e^{i\theta_n} + v_s e^{i\varphi} dt_n . \tag{3}$$

This equation is coupled with an MC procedure that samples PDFs for CG flash interval time and position to determine when and where CG strikes occur relative to the moving cell center. Thus, the FTPM model generates a time series of flashes at positions around the moving storm cell, simulating the time and ground position distribution of strikes caused by a localized storm cell.

The FTPM simulates individual days by treating the number of storms in a day as random variable storms, with start times distributed as determined by the NLDN data. The time and position of CG lightning flashes resulting from the storm are tracked using the cell model described previously. All parameters in the model, such as the starting location of the storm and its speed, direction, and duration, are treated as random variables. The FTPM provides a PDF for the number of flashes in the accumulation area. The accumulation area is much larger than the attraction area of the firing site itself. Use of an accumulation area allows fewer simulation runs for a given confidence level. The validity of this technique relies on the known uniform flash density in the region around the firing site. The FTPM also provides a PDF for the time spent on alert as a result of a user-defined set of lightning risk management rules.

This approach provides a simulation of thunderstorm activity that closely reproduces the observed spatial and temporal distributions of lightning strikes around DARHT without any “knobs.” This result merits further discussion. Our model for the occurrence of a storm (start time and range from DARHT), its subsequent motion, and the spatial and temporal flash characteristics associated with it are relatively simple. All 14 independent random variables, several of which are correlated, are used in the FTPM. Whether such a simplification of complex electrical storms would be suffficient was not clear a priori. Additionally, the PDFs for most storm-centered variables were deduced from NLDN data represented in a fixed coordinate system. This procedure required making assumptions about what defines a storm in terms of available NLDN parameters—interflash times and separation. Again, the sensitivity of the PDFs to these assumptions was not known before the analysis. We found that the model simulations yield an average flash density at DARHT that is well within the range of the density calculated from the NLDN data. Because the flash density is the principal determinant of the probability of a strike at a location, the FTPM risk calculations will be relatively close to those deduced from NLDN data. Additional validation analysis showed that the relative proportions of storm types (for example, warning only or warning followed by alert) calculated by the FTPM were almost identical to those derived from the NLDN analysis. This means that the evaluation of time-dependent factors associated with alert and warning times will be realistic.

4. CALCULATING THE CONSEQUENCES AND RISK FROM LIGHTNING

The portion of the risk model dealing with the LRMS includes a detection model that observes the FTPM-generated flashes and issues the proper warning based on the CG position relative to DARHT. The efficiency of the NLDN is a parameter that can be modified. An efficiency of less than one means that some NLDN flashes will escape detection. In addition to warning times, the model calculates when all-clear conditions are met, thus providing a measure of the productive time lost for each simulated storm.

The RM is used to calculate the probability distribution of the consequences of lightning during a day of operations, which requires a model of what happens when a lightning strike occurs at the firing site. The LRM calculates the risk for each of a set of lightning accident scenarios. Each scenario is a possible outcome of a lightning strike under specified circumstances. The probability associated with each scenario is calculated based on the probability of one or more lightning strikes on the firing site and the conditional probability of realizing the enabling conditions. This model is in the form of conditional probabilities of fatality for each person at the firing site or in a more remote exposed location given that an HEVR does or does not occur.

Fatalities as a result of lightning are the consequences currently included in the LRM. These consequences can be the result of lightning only or the result of secondary events, such as lightning-induced HEVRs. The number of fatalities realized during a strike is strongly dependent on the number of people present at the firing site when the strike occurs. This number is dependent on the time of day and on any lightning management procedures, such as a lightning warning, in effect at the time of the strike. As was mentioned previously, the FTPM provides an indication of when warning conditions are met, and so evacuation procedures can be modeled. The actions taken upon warning can be varied to model a wide variety of actions, such as seeking shelter and reducing the number at risk. Time delays are included as parameters. The effect of the model is to modify the number of people at risk as a function of time after a warning or the subsequent all-clear signal is received.

In the current application, an important part of the LRM is the conditional probability of an HEVR given a firing-site lightning strike. The estimate for this probability is based on explosives engineers' and scientists' interpretations of tests and other accumulated experience. An important aspect of the expected consequence is the number of people who are at risk of injury and the cost of the equipment at risk of damage. Both the number of people at risk and the possible lightning-induced HEVR modes depend on the phase of the operation. The ability to model multiple phases of operation is included in the LRM. Using this information and the strike frequency provided by the FTPM, the model computes the expected number of fatalities resulting from lightning during HE operations.

The consequence model includes both people killed directly by lightning and those killed by lightning-induced HEVR events. The fraction of nearby people directly killed by a lightning strike is a random variable that can be adjusted to fit different circumstances. Strikes that attach in some areas of the firing site are more likely to induce HEVRs than are attachments to other locations. The FTPM provides the number of strikes in a area that includes the entire firing site. The actual location of the attachment within this area is based on the attraction area of the experiment and other equipment and people in the area. An example of an attraction area for an experiment with a central HE charge and four surrounding instrument towers is shown in Fig. 3.

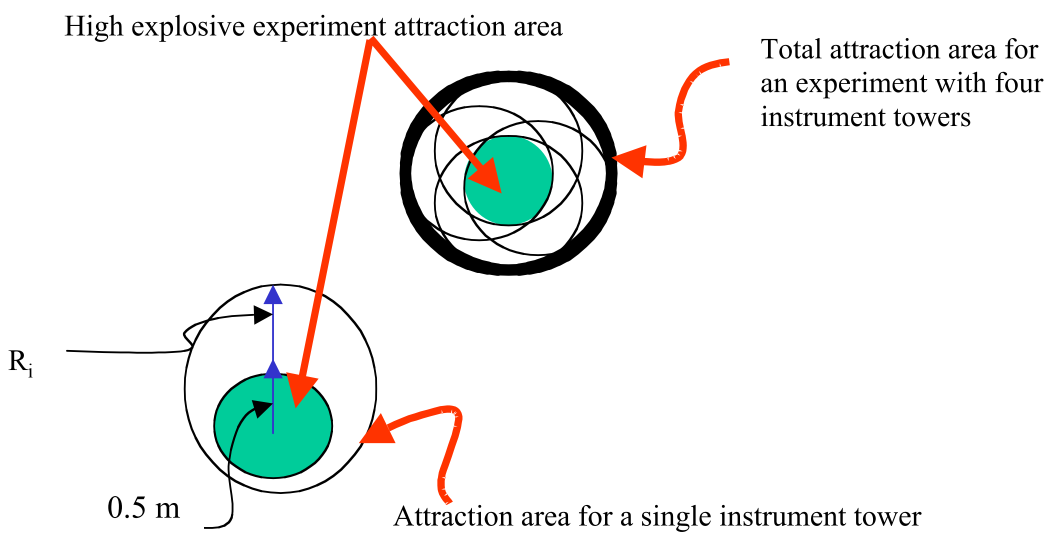

Fig. 3. Example of a complex attraction area.

The probability of an HEVR given a lightning strike is estimated based on tests with HE. These tests include induced lighting strikes on the explosive charges and simulated lightning currents in detonators. The typical assumption used in the model is that if an HEVR is induced, all persons in the immediate vicinity are killed, and some fraction of the personnel at a distance from the firing site proper are killed as well. These fatality fractions are adjustable parameters in the model and can be altered, if required.

The LRM has the capability to estimate the work time lost as a result of lightning alerts, mean warning time between alert and the first nearby strike, and many other useful statistics. The model calculates a PDF for the number of strikes at the firing site during a user-defined operational day and the expected consequences resulting from such a strike. The capability of the model allows a comparison of different risk control strategies by providing estimates of the changes in risk and lost time resulting from variations in operations or engineering features.

5. COMPARING LIGHTNING RISK

MC simulations with the RM were performed to determine the risk for HE operations at DARHT during the summer. The calculated fatality risk is approximately 5×10^{-6} fatalities per experiment day. To put this into perspective, a set of comparison calculations was done for the following cases:

1. HE experiment with no LDWS controls,
2. noon workers going to lunch,
3. workers leaving at the end of the day, and
4. operation of a drill rig.

The control procedures for these cases are essentially normal "flash-bang"-based warning recommended by the American Meteorological Society (2002). The absolute values of risk are useful in determining how much risk is being accepted. These values also provide comparison points for other societal and LANL risks. The results of these calculations are shown in Fig. 4. Note that the risk for the base case here (HE with LDWS) has the lowest risk. Even without lightning risk management measures in place, the fatality risk for lightning at the DARHT site is comparable to or below other implicitly accepted lightning risks at LANL. This is the case because of the rarity of lightning strikes on objects with small attraction areas such as the firing site and because the number of fatalities is limited in the event of a strike to the small number of personnel present at the firing point. We found that the presence of HE at the firing site was not a major contributor to fatality risk. This conclusion was considered somewhat surprising in light of preanalysis expectations. The explanation can be traced to the difficulty in producing lightning-induced initiation of the HE during the phase of the experiments when the most people are present. The phase of the operation when the probability of a lightning strike causing HE initiation is greatest occurs when few, if any, people are on the firing site.

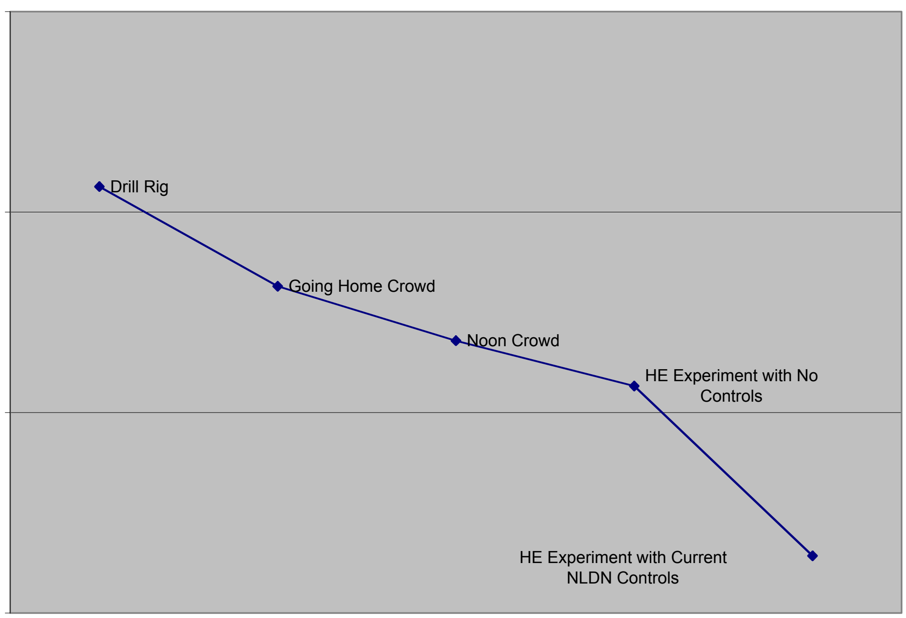

Fig. 4. Lightning-risk comparison for various activities.

6. THE EFFECT OF PROCEDURES ON RISK/COST

Changes in relative risk can be used to determine optimal risk management strategies. The choice of strategy is constrained to be consistent with a given level of acceptable risk. For the analysis here, the level of acceptable risk was taken to be the base case with the LDWS and as-is procedures. We performed risk calculations for a variety of different risk management strategies with this constraint. The three major independent control variables are the all-clear radius, the all-clear interval, and the alert radius. Changes in one or more of these parameters affect both the risk and the time on alert. Effective control strategies will minimize both.

Figure 5 shows the relative risk as a function of the all-clear radius. We use relative risk, the ratio of the number of flashes when personnel are exposed to the total number of flashes in the accumulation zone, for the ordinate in Fig. 5. This relative risk varies in the same way as fatality risk but is more convenient for control parameter comparisons. Recall that the all-clear radius, 16.1 km for the base case, is greater than the alert radius, 10 km. The all-clear radius sets the start time for the all-clear interval. As expected, Fig. 5 indicates that the risk decreases as the all-clear radius increases. The statistical variation (90% confidence) in relative risk arising from the MC simulation is reflected by the error bars in the plot. It can be seen that decreasing the all-clear radius to 10 km does not increase the relative risk. Figure 6 shows the corresponding effect for mean time on alert. A net savings of approximately 5 min. per alert is realized by decreasing the alert radius to 10 km.

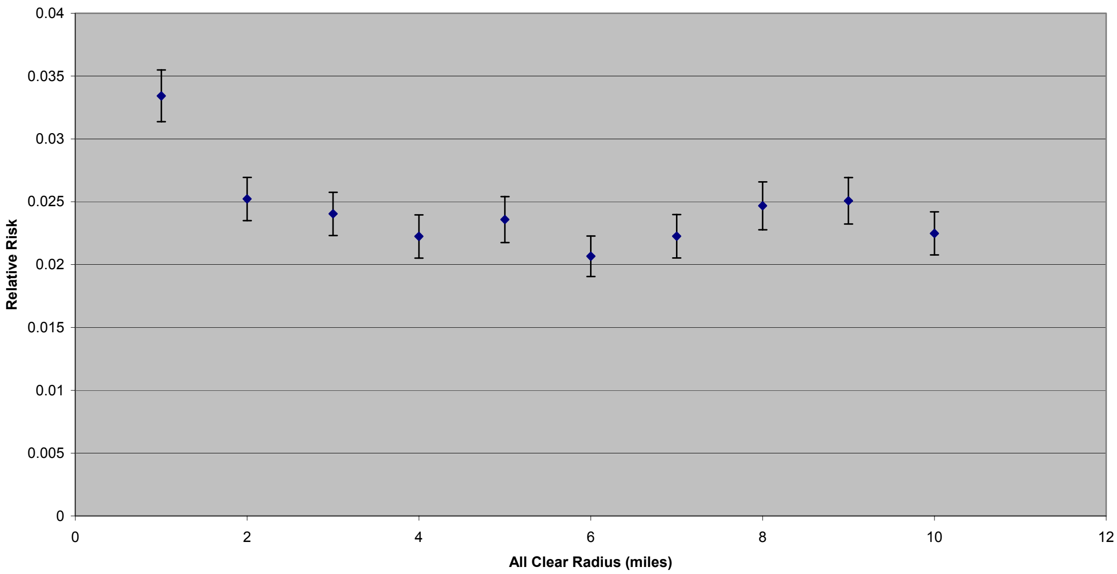

Fig. 5. Risk as a function of all-clear radius; 10-km (6-mile) alert radius, 30-min all-clear interval.

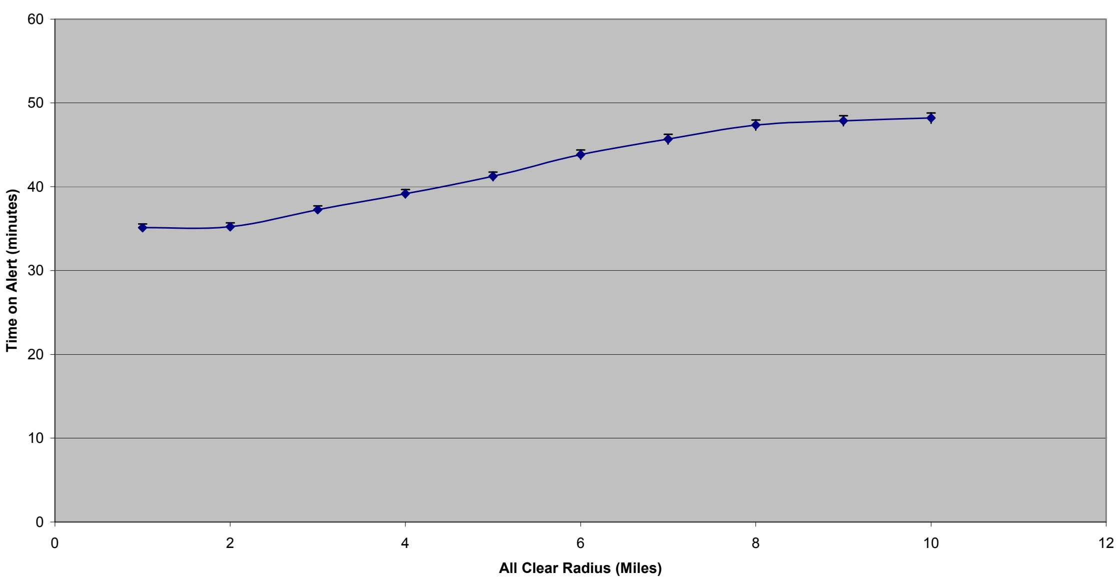

Fig. 6. Mean time on alert as a function of all-clear radius; 10-km (6-mile) alert radius, 30-min all-clear interval.

Figures 7 and 8 show the corresponding results with the all-clear interval as the independent parameter. For these calculations, the all-clear radius was set to 10 km. An all-clear interval of 15–20 min.

provides a considerable reduction in mean time on alert without an increase in risk. An additional consideration in setting the all-clear interval is the need to avoid the "yo-yo" effect (that is, returning to work and having to evacuate again almost immediately). We tested the 20-min. all-clear interval against the historical record base and determined that the yo-yo effect would not be significant.

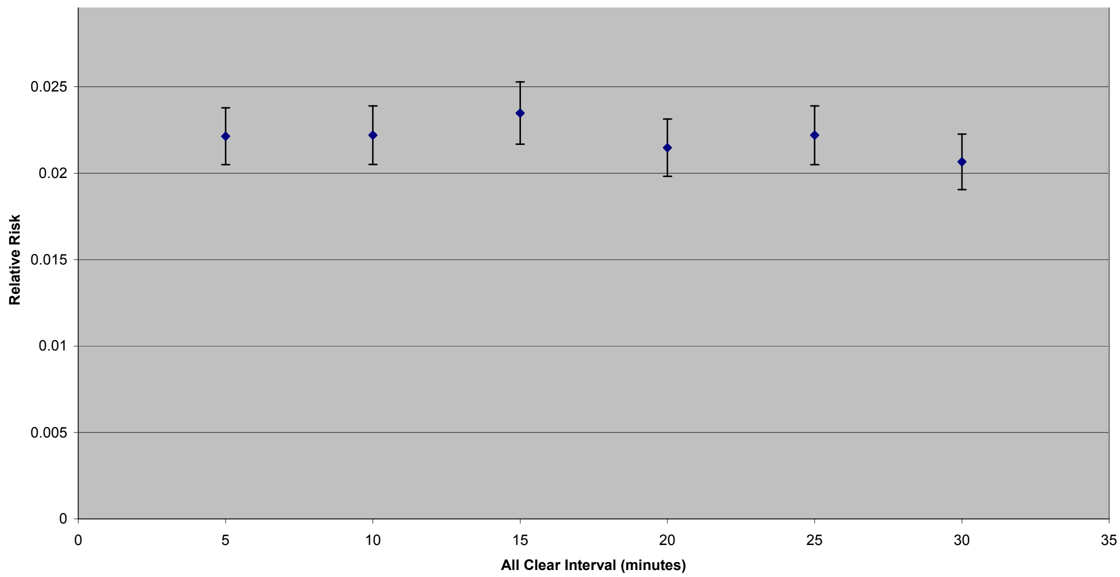

Fig. 7. Risk as a function of all-clear interval; 10-km (6-mile) all-clear radius.

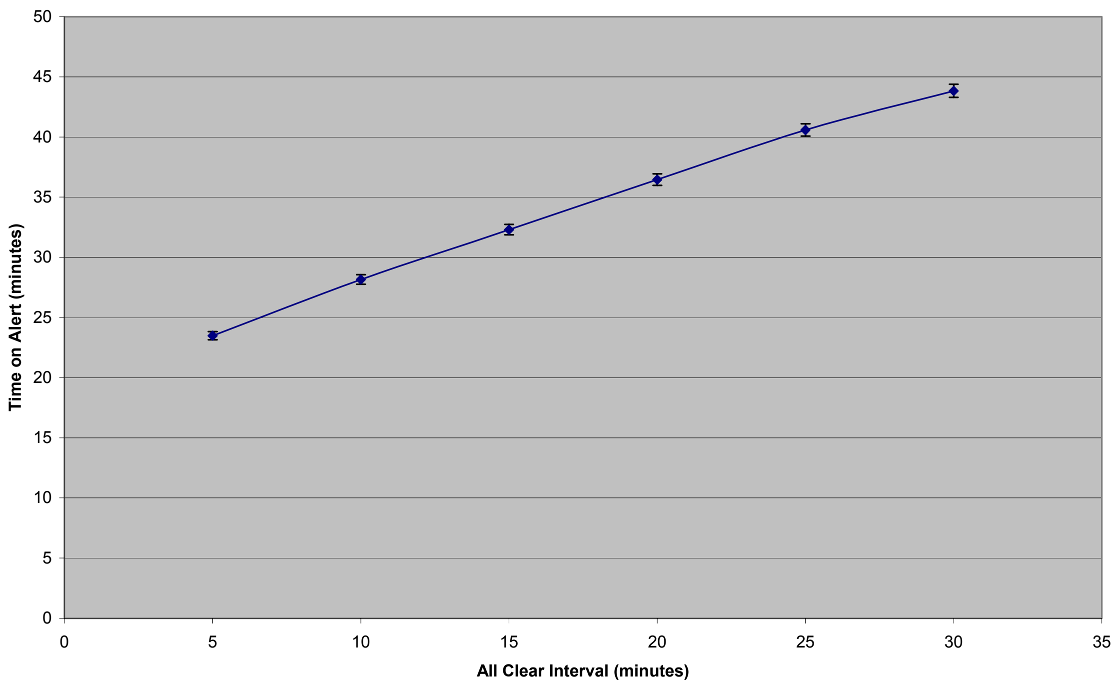

Fig. 8. Mean time on alert as a function of all-clear interval; 10-km (6-mile) all-clear radius.

The effect of alert radius on risk is shown in Fig. 9 and the effect on time on alert in Fig. 10. Note that decreasing the alert radius from 10 to 8.3 km increases the risk by about 25%; however, this change also leads to a reduction in time on alert of approximately 17 min. (40%). Because the risk is low, such a tradeoff may be a realistic option.

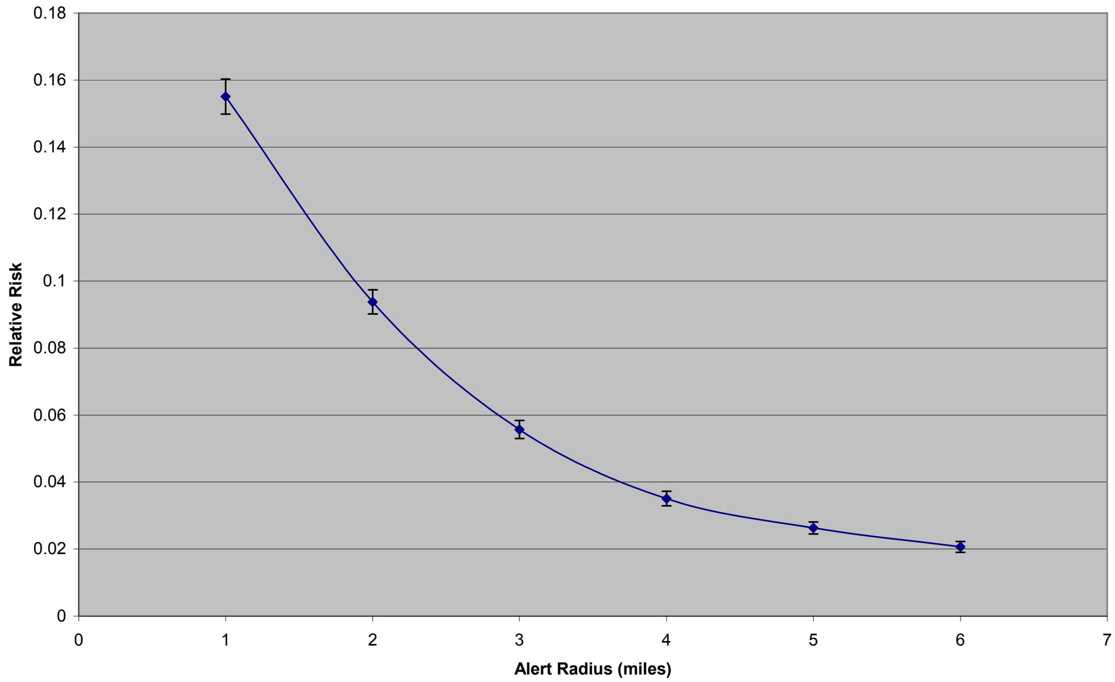

Fig. 9. Risk as a function of alert radius; the all-clear radius equals the alert radius, and the all-clear interval is 20 min.

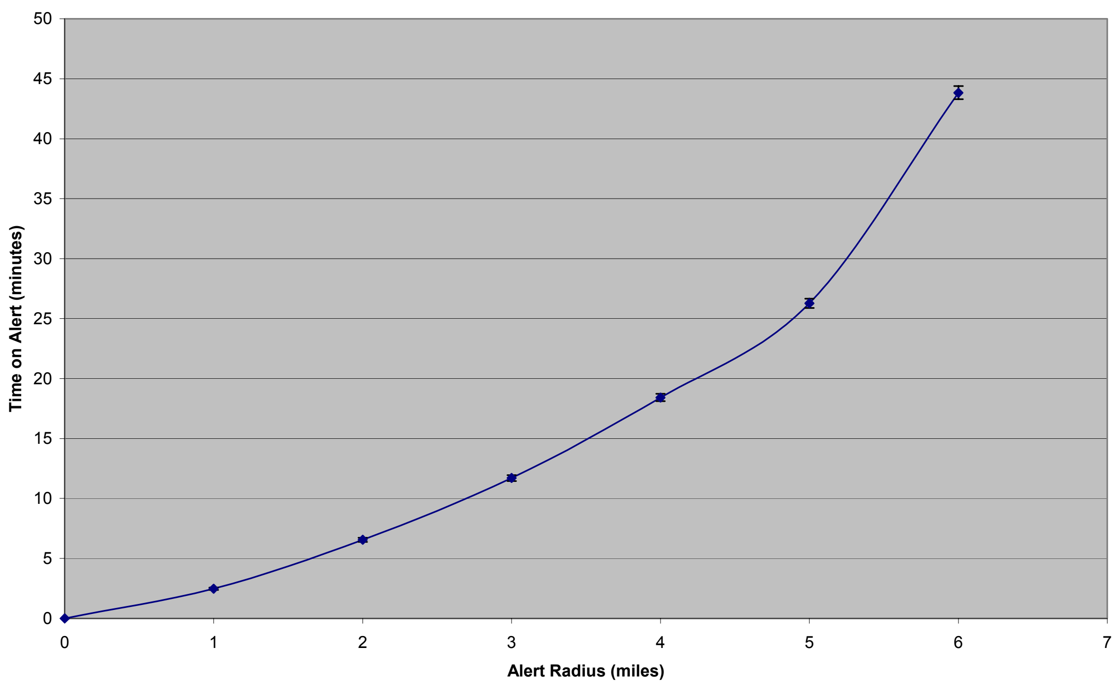

Fig. 10. Mean time on alert as a function of alert radius.

Other options for improving the risk/benefit ratio without increasing risk also exist. For example, if lightning-safe detonators were used on experiments, then the alert radius could be reduced as suggested previously with no increase in risk. Thunderstorms are more probable in the afternoon, so starting work at the firing site early in the day can reduce the exposure of personnel to lightning absent any other LRMS change. A summary of calculations showing the individual effect of these options is presented in Fig. 11.

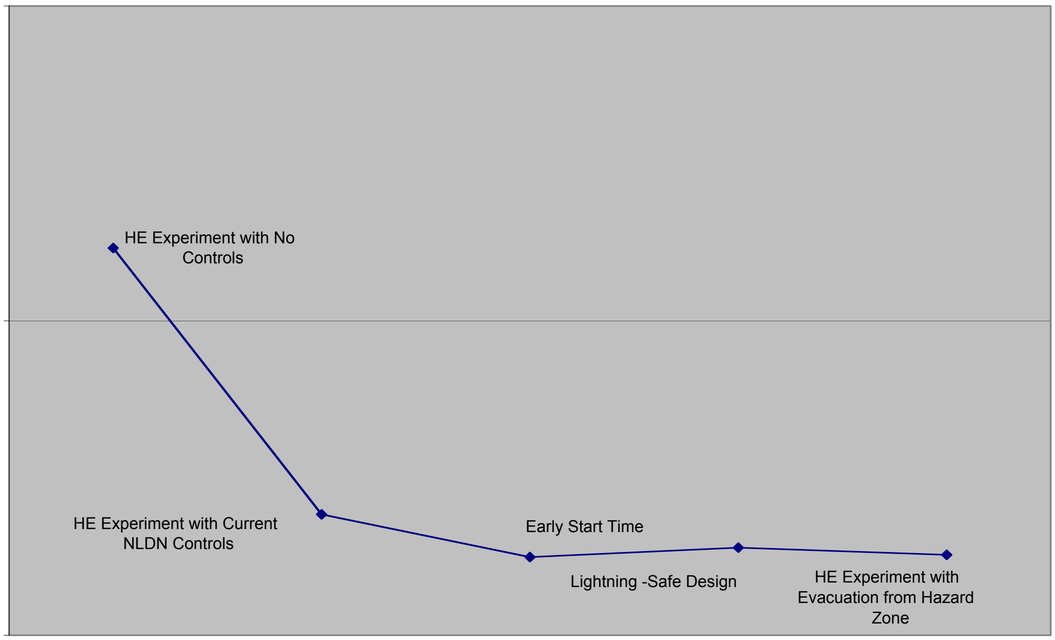

Fig. 11. Lightning-risk reduction for various control strategies.

7. CONCLUSIONS

Lightning is an obvious potential hazard associated with outdoor HE operations. This statement is particularly true at the DARHT facility at LANL because of the size and importance of the experiments performed there and the high flash densities that exist during the monsoon season. The localized nature of the thunderstorms in close proximity to mountains complicates the job of lightning warning and the design of procedures to effectively reduce risk. The actual risk reduction associated with the use of an LDWS under these circumstances has been analyzed. Our approach uses PRA and MC simulation. The use of a simulation model allows for the study of the interaction of the storm, the HE, the LDWS, and the control procedures.

We found that the worker risk associated with lightning was actually quite low despite the high flash densities. This is explained by the fact that the area of interest is quite small and that a few flashes at most will occur before an evacuation can take place. The contribution of the HE-to-worker risk is small relative to the risk from lightning alone. These results lead to the important conclusion that the value of the LDWS/controls must be understood in terms of the costs associated with the time spent under alert. The PRA/MC methods used here allow for a systematic analysis of the changes in risk and cost associated with the procedures in place to provide alerts and warnings. We found that changes in the controls could lead to significant cost savings without an increase in risk. Although the problem studied here is quite specific in terms of location and facility, the methodology is quite general. It can be applied for locations where sufficient statistical data exist to allow the MC representation of storm behavior to be constructed. Although the response of systems that can contribute to lightning-related hazards will be problem specific, the use of PRA provides a powerful tool to understand and quantify the resulting risks.

The inherently low risk posed by lightning implies that any imposed controls that increase the cost of operations will have a high cost per averted fatality and should be considered carefully before implementation. For example, the potential reduction in risk afforded by using EFMs to alert for quickly forming or short duration storms must be considered in the context of exposed population, evacuation times, and the possibility of increased time on alert arising from false alarms. Another consideration is the possibly significant increases in risk resulting from higher human error rates because of lost work time. Such error-rate increases can occur because of added time shortage stress resulting from lightning-induced delays, as well as several other causes related to delays (Williams, 1988).

The analysis results presented here are specific to the DARHT facility and the localized storms associated with the southwest monsoon in Los Alamos; however, the basic model has sufficient flexibility to evaluate the risk associated with large frontal storms. The assumptions of circular cell geometry, constant storm velocity, and azimuthally symmetric flash distribution—found to be suitable for the DARHT analysis—can be relaxed if the available location-specific NLDN data warrant. Multiple sites of interest could be treated in an integrated analysis as well. Finally, the extension to other types of secondary effects, such as fires and gas explosions encountered in many outdoor industrial operations, is straightforward.

7. REFERENCES

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