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ANALYSIS OF LIGHTNING-RELATED RISK IN OUTDOOR HIGH EXPLOSIVE RESEARCH

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1. INTRODUCTION

The behavior of materials at high strain rates can be studied using high explosives (HE) as an energy source. Such hydrodynamic experiments may be performed on full-scale systems, requiring kilogram quantities of HE and therefore are performed at outdoor facilities. One such facility is DARHT—the Dual-Axis Radiographic Hydrodynamic Test facility located at Los Alamos National Laboratory in northern New Mexico. DARHT is a very large flash x-ray machine. The high-intensity, short-duration x-ray pulses are beamed through the hydrodynamic experiment to an x-ray camera. Density variations in the materials produce variations in the transmitted beam that are recorded by the camera. The information in these images is used to understand the basic behavior of materials subjected to very high dynamic pressures and to evaluate the accuracy of computer codes used to model the associated phenomena.

DARHT became operational in the summer of 2000. During the construction, a hazard assessment (HA) was performed for the firing site—the aboveground area centered about the axes of the two x-ray beams where the hydrodynamic experiment containing the HE and associated diagnostic and support equipment are located. The HA identified two accident scenarios involving lightning-induced high explosive violent reactions (HEVRs). If an HEVR were to occur with personnel at the firing site, fatalities would be very likely. The experiments of concern use electrical detonators to initiate the HE, and it is for this reason that explosive safety standards such as the Department of Energy (DOE) Explosive Safety Manual (1988) and Laboratory procedures address lightning specifically and in detail. Before operations at DARHT, a lightning alert—requiring personnel to evacuate a firing site and seek shelter—was declared based on visual observation by the firing site leader. (A firing site leader is responsible for the operations at a firing site and ensures that all applicable safety procedures are followed.) An alert was declared based uon visual/audible (flash/bang) indication that cloud-to-ground lightning is occurring within 5 km (3 miles). Although the HA analysts concluded that this approach would produce an acceptably safe operation, it was pointed out that better lightning warning systems were readily available and that a new system should be acquired. This recommendation was supported by the reviewers of the HA and the decision to purchase a Lightning Detection and Warning System (LDWS) was approved by the facility operators.

Hazard analysis is intended to be used as a screening tool to identify high-risk situations. No attempt was made to quantify the prior risk or the risk reduction resulting from the use of an improved LDWS. By the same token, issues related to risk-cost ratio remained outside the scope of the analysis. The costs of interest here are primarily associated with time spent on alert—when experimental activities cease—rather than the capital or operating costs for the LDWS. The LDWS described below became operational in the summer of 2001. Operation, albeit with the usual start-up problems, was judged successful. However, it was apparent that the costs associated with delays in operations were increased over the old procedures. Therefore, the questions of risk reduction and risk-cost ratio increased in significance, and answers were needed.

Issues associated with risk quantification can be addressed using probabilistic risk assessment (PRA) (Thomson 1987), a well-established technique used for assessing complex systems such as nuclear reactors and the Space Shuttle. Ideally, PRA is used in conjunction with an HA to examine "high-risk" scenarios (Bott 1996). For various reasons outside the scope of this paper, the decision to use PRA for the DARHT lightning-induced risk problem was not made until 2002.

PRA is used when the risk is uncertain. The uncertainty may be aleatory—associated with the stochastic nature of physical processes—or epistemic—arising from imperfect knowledge. Thunderstorms, the associated lightning, and the response of HE to lightning all exhibit aleatory behavior, and therefore, the risk is uncertain. Uncertainty in risk is estimated by treating the key parameters in these processes as random variables described by probability density functions (PDF). When the number of parameters is large, as is the case here, the PDF for the risk is obtained using Monte Carlo (MC) simulation (Kalos 1986). That is, many individual simulations of the stochastic processes are calculated. In each trial, all of the input random variables are determined by "rolling the dice," with the outcomes determined by the individual PDFs. Each simulation results in a separate estimate for the risk. In this paper, we use PRA/MC to estimate lightning risk associated with high explosive operations. The MC model also provides the capability to examine how changes in LDWS performance and the controls used to declare alert and all-clear states affect the risk and the operational costs arising from lightning. We also describe how this type of analysis was performed for the DARHT facility. We show that the overall risk is low and the contribution of the HE is relatively small and discuss the effect of control strategies on risk/cost and risk/benefit ratios.

2. LIGHTNING CHARACTERISTICS

Lightning storm frequency, duration, and intensity are a strongly dependent on location. DARHT is located on the Pajarito Plateau at an elevation of 2190 m (7180 ft). 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 [3097 m (10,160 ft)] and Pajarito Mountain [3182 m (10440 ft)], both approximately 12 km (7 mi) away. Just to the west of the Sierra de Los Valles is the Valle Grande, the remaining caldera of the volcano. The lower edge of the plateau is approximately 10 km to the east [elevation 1950 m (6400 ft)], where it meets the Rio Grande River in White Rock Canyon (elevation 1670 m). Approximately 25 km farther to the east are the Sangre de Cristo Mountains.

A large fraction of the lightning storms in Northern New Mexico occur during the summer months as a result of the Southwest monsoon. The monsoon is characterized by the movement of humid air from the Gulf of California and (in New Mexico) the Gulf of Mexico (Watson 1993a) and typically begins 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 the risk and the effectiveness of the LDWS.

Lightning exposure commonly is expressed in terms of flash rate density—flashes per unit area per unit time. Cloud-to-ground flashes are detected by the National Lightning Detection Network (NLDN) (Cummins 1997). The NLDN uses-time-of-arrival and magnetic-direction-finding data from a collection of over 100 sensors to provide timing, location, and multiplicity information for flashes detected in the contiguous United States. The current NLDN has a flash-detection efficiency of 0.8 to 0.9, depending on the peak flash current and location. The nominal location accuracy is 0.5 km.

NLDN data for the years 1994 to 1999 and 2001 were provided to LANL by Global Atmospherics (now Viasala-GAI), the operator of the NLDN and the supplier of the Los Alamos LDWS described in the next section. The average flash density in an area with a radius of 10 km (6 mi) centered about DARHT is 0.0097 F/km^2/D (0.04 F/mi^2/D) or an annual rate of about 3-1/2 flashes per square kilometer. The 10-km radius corresponds to the alert circle defined for the LDWS as discussed below. 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 number 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 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 flash-rate densities at DARHT are quite high and well above national averages.

The MC risk model simulates thunderstorm activity for a weekday during July or August. The random behavior of storms that are generated, move in the vicinity of DARHT, and produce a spatial and temporal flash distribution must be reflected in the model. This requires that accurate PDFs for the parameters of interest must be determined. The fundamental units from which all of the parameters will be estimated are discrete storms. Note that the natural coordinate system for modeling a storm is one that moves with the storm center. However, the NLDN data are in a coordinate system that moves with the Earth. Therefore, in the absence of other sensor data such as Doppler radar, the definition of a storm must be based on the relationship of observed flashes. Finke (1999) has reported the use of a space–time correlation technique to obtain storm-centered measurements for large frontal-type storms. We have adapted this technique for the study of localized storms and will report on it in a future paper. In this paper, we use the criterion that two flashes, F_i, F_j' belong to the same storm if

$$s_i, s_j \leq 16.1 \cdots \text{km} \qquad t_j - t_i \leq 1800 \cdots \text{s} \qquad (1)$$

where s is the distance measured from DARHT and t is the time. One drawback to this approach is that flashes will be considered to be part of the same storm if lightning activity from multiple cells is present in the same time window. However, because we are interested in the statistical properties of storm characteristics, these effects will be incorporated as small second-order variations in the storm simulation. For each parameter that is treated as a random variable, a PDF or its integral, the Cumulative Distribution Function (CDF), is needed. These parameters are discussed in Section 4. We consider here a single parameter whose statistical representation plays a significant role in the risk model. How long does a thunderstorm last? This problem was examined previously by Robinson and Easterling (1988) using limited pre-NLDN data. A storm defined by Eq. 1 can consist of many, a few, or only a single flash. In the case of a single flash, the storm is assigned a duration of 120 s. Figure 1 shows the PDF for storm duration. It is clear that the density is bimodal. With probability p = 0.29, a storm consists of a single flash. The bimodal nature of the PDF will affect lightning risk and the ability of the NLDN data to provide reliable warning advisories. If one removes the single-flash storms from consideration then the mean

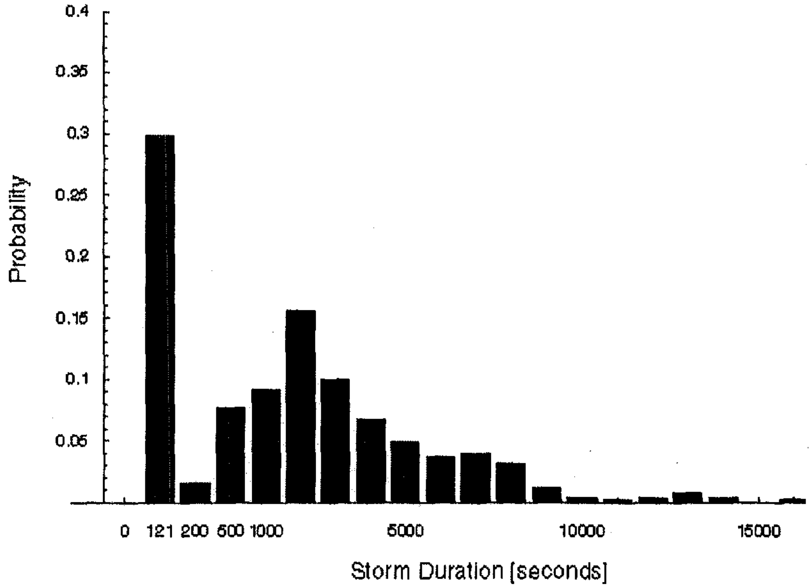

Figure 1. Probability density function for storm duration in seconds.

multi-flash storm duration is $\mu(\tau) = 2772$ s. The duration PDF for a storm with multiple flashes is well represented by a shifted exponential (Christensen 1984):

$$\mathrm{PDF}(x) = \frac{1}{b} e^{-\left(\frac{x-a}{b}\right)} \ldots x > b \qquad (2)$$

with $b = 121$ and $a = (\mu_S) + b$. In some cases, the CDF is described using a histogram rather than an analytical function when there is no strong theoretical justification for a particular function or when no acceptable fit to a function could be obtained.

3. LIGHTNING DETECTION AND WARNING SYSTEM

The LDWS used at Los Alamos is a Precision Lightning Warning System from Visalia-GAI of Tucson, Arizona. The system as originally configured consisted of a satellite link to the 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 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 in 2002 to provide increased lightning protection at several other facilities located a number of kilometers from DARHT. 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 by the Dynamic Experimentation (DX) Division at Los Alamos. DX is the organization responsible for HE operations and 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 flash within 10 km of DARHT. When an alert is declared the firing site must be evacuated promptly, and personnel 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 should 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. The performance of the EFMs during the 2001 lightning season was hindered by various sensor and networking issues. For this reason, we discuss mainly the NLDN component of the LDWS and the associated procedures. 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 below.

4. FIRING SITE LIGHTNING-RISK MODEL

The firing site lightning-risk model (FSRM) is used to calculate the probability distribution of the consequences of lightning during a day of operations. The model produces such statistics as the expected number of fatalities and the expected cost in damaged equipment resulting from lightning during HE operations. The FSRM also 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 number of strikes is supplied by a Monte Carlo simulation called the Flash Time-Position Model (FTPM). With the output of the FTPM, the expected consequences are computed using an algorithm called the Lightning Risk Model (LRM).

The FSRM can accommodate different alert criteria and seasonal and diurnal variations in lightning flash rates and can be adapted to different localities by using local flash data. It has the flexibility to model varying modes of operation and can accommodate phased missions in which operational and risk parameters change with time. The model includes both the direct effects of lightning and secondary effects such as actuation of explosives. Although the FSRM calculates risk on a per-day basis, multiple days can be strung together to create risk models of multiple-day operations. The FSRM includes the effects of detector efficiency, evacuation delay after alert and multiple spatially separated strokes from a single flash. Uncertainty in virtually all input values can be accommodated through PDFs.

The FTPM part of the model uses a Monte Carlo simulation based on observed lightning data and behavior in the vicinity of the target (in the current application, the DARHT firing site). The FTPM provides a PDF for the number of flashes in a circular area surrounding the firing site called the accumulation area. The use of the accumulation area is based on the observed uniformity of strikes in the region around the firing site. Use of the accumulation area allows fewer simulation runs for a given accuracy. 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.

The FTPM was developed to provide sufficient computational capability to address risk management strategies that include warning and evacuation. This problem includes imbedded time-position dependencies that must be treated for a reasonable solution. The capability of the model allows 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.

The FTPM reproduces observed lightning data around DARHT very well. The model contains no "knobs." All parameters have a physical or observational basis. Most of the parameter values are calculated from local NLDN data. A few parameters are based on published results that are generally applicable to lightning in a variety of locations. The FTPM simulation runs at about 5–10 min of PC CPU time per 10,000 days of simulation, depending on the options exercised.

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, the conditional probability of realizing the enabling conditions, and the conditional probability of different consequences. Fatality and equipment damage risk are calculated based on the numbers of people and value of equipment at risk. The scenario risk values are summed to estimate the total risk.

The LRM begins by calculating the probability of one or more strikes at the firing site. This probability is calculated using the number of strikes in the accumulation area supplied by the FTPM. The calculation uses the number of accumulation strikes and the ratio of the FSAA to the accumulation area as the parameters in a binomial model.

Fatalities and equipment loss 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 HEVR. In the current application, an important part of the LRM is the conditional probability of HEVR given a firing-site lightning strike. The estimate for this probability is based on explosives engineers' and scientists' interpretation 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.

5. RESULTS OF ANALYSIS

Risk and cost estimates provide a valuable input to rational decision-making. The output of the LRM provides both risk and cost estimates in the form of work-time lost because of lightning alert. Warning times before flashes in the vicinity of the firing site also are provided. The reduction in risk accruing from lightning-safe detonator systems or using additional warning devices such as EFM also can be estimated.

Relative changes in the risk and time on alert arising from lightning and the risk management options may be explored using the LRM. The absolute values of risk and constraints are useful in determining how much risk is being accepted and how much changes in risk cost or save per averted fatality or unit of monetary loss. These values also provide comparison points for other societal and LANL risks. Relative risk changes are used in determining optimal risk management strategies consistent with a given level of acceptable risk. Any of the risk management parameters in the model can be varied to reflect changes in controls. In addition, the effects of the time of day that the work is performed, engineered features that affect the probability of HEVR given a strike, and physical lightning protection devices may be modeled.

Risk calculations were performed for a variety of different risk-management strategies for comparison and benchmarking. Impact-benefit ratios for different risk-management strategies and tactics can be examined using the LRM. For example, the cost per averted fatality or the cost per averted dollar loss can be calculated from the LRM outputs for simulations with two different risk-management strategies.

We have made a number of observations based on our calculations. Three important ones are listed below.

1. The fatality risk for lightning at the DARHT site is low. This arises from the rarity of lightning strikes on objects with small attraction areas such as the firing site and on the limited number of fatalities resulting when a strike does occur. This inherently low risk 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. This consideration should include 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).
2. The HE is not the major contributor to fatality risk. This somewhat surprising conclusion can be traced to the difficulty in producing lightning-induced initiation of the HE during that phase of the work when the most people are present. The phase of the operation when the probability of a lightning strike causing HE initiation is greatest occurs while few if any people are on the firing site.
3. Many opportunities for reducing the time spent on alert, without increasing the fatality risk, can be found by varying the lightning risk-management controls. For example, lightning-safe detonators can be used to relax other control parameters such as the alert range with no increase in fatality risk.

6. CONCLUSIONS

Lightning is an obvious potential hazard associated with HE operations. This is particularly true at the DARHT facility at Los Alamos 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 will occur at most before an evacuation can take place. The contribution of the HE to worker risk is relatively 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 exists 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.

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