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Indirect Lightning Safety Assessment Methodology

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1. Introduction

Lightning is a safety hazard for high-explosives (HE) and their detonators. In the last couple of decades, DOE facilities where HE is manufactured, assembled, stored or disassembled have been turned into Faraday-cage structures to protect against lightning currents [1]. If HE is adequately separated from the walls of the facility that is struck by lightning, electrons discharged from the clouds should not reach the HE components.

However, the current flowing from the strike point through the rebar of the building to the earth will create electromagnetic (EM) fields in the facility. Like an antenna in a radio receiver, the metal cable of a detonator can extract energy from the EM fields. This coupling of radio frequency (RF) energy to explosive components is an indirect effect of lightning. The most sensitive component is typically a detonator, and the safety concern is initiation of the HE.

The methodology for estimating the risk from indirect lighting effects will be presented. It has two parts: a method to determine the likelihood of a detonation given a lightning strike, and an approach for estimating the likelihood of a strike. The results of these two parts produce an overall probability of a detonation.

The probability calculations are complex for five reasons: (1) lightning strikes are stochastic and relatively rare, (2) the quality of the Faraday cage varies from one facility to the next, (3) RF coupling is inherently a complex subject, (4) performance data for abnormally stressed detonators is scarce, and (5) the arc plasma physics is not well understood. Therefore, a rigorous mathematical analysis would be too complex. Instead, our methodology takes a more practical approach combining rigorous mathematical calculations where possible with empirical data when necessary. Where there is uncertainty, we compensate with conservative approximations. The goal is to determine a conservative estimate of the odds of a detonation.

In Section 2, the methodology will be explained. This report will discuss topics at a high-level. The reasons for selecting an approach will be justified. For those interested in technical details, references will be provided. In Section 3, a simple hypothetical example will be given to reinforce the concepts. While the methodology will touch on all the items shown in Figure 1, the focus of this report is the indirect effect, i.e., determining the odds of a detonation from given EM fields. Professor Martin Uman from the University of Florida has been characterizing and defining extreme lightning strikes [2]. Using Professor Uman's research, Dr. Kimball Merewether at Sandia National Laboratory in Albuquerque calculated the EM fields inside a Faraday-cage type facility, when the facility is struck by lightning. In the following examples we will use Dr. Merewether's calculations from a poor quality Faraday cage as the input for the RF coupling analysis.

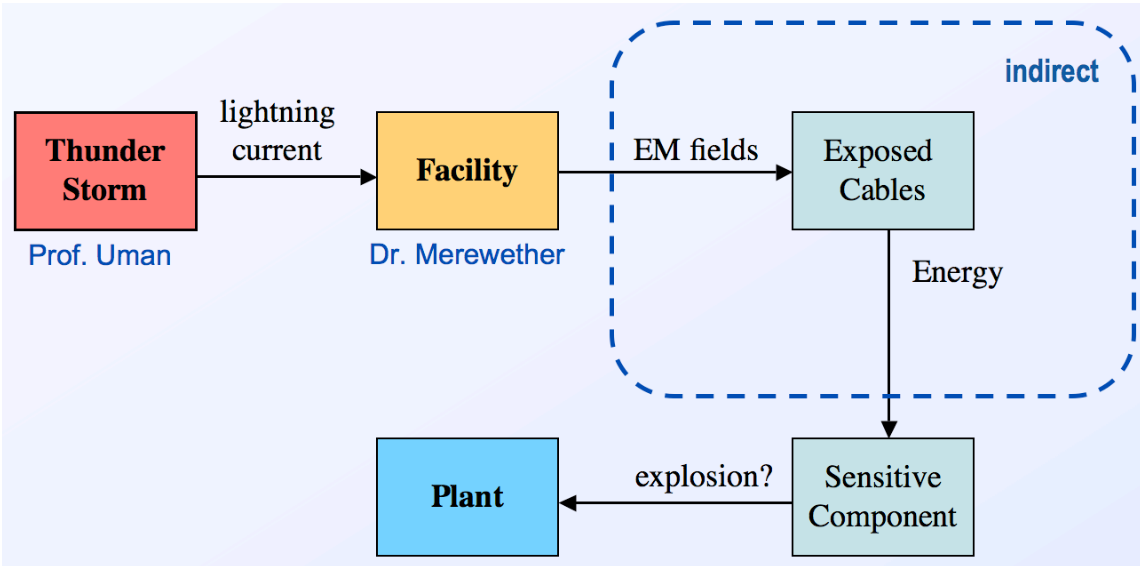

Figure 1.1. A lightning strike to a facility will create EM fields that convey energy to sensitive HE components.

While the RF coupling can be accurately computed for a given work configuration, determining the exact probability of an explosion is nearly impossible because of the randomness of lighting, the numerous construction features of a facility, the numerous RF coupling configurations, and the variation in detonator sensitivity to electrical energy. Instead of asking if a process is safe, a better question is: "How safe?" Even a rough (an order-of-magnitude) estimate of probability is valuable for planning and refining the analysis and is essential for understanding the risks.

2. Methodology

The methodology borrows a couple terms, stress and strength, from mechanical testing of metals that should be easy to understand. The heart of the safety assessment methodology is a probabilistic comparison of the stresses caused by lightning on critical explosive components against their strength to withstand the stresses without detonation. (See Figure 2.1.) For example, let's describe a standard detonator cable setup for a simple explosive study, where there will be one detonator and the cable. The energy from this detonator cable, or "antenna", deposited on the detonator is compared against the threshold energy for initiating the explosive process. This probability calculation assumes that there is a lightning strike. The bottom half of the Figure 2.1 accounts for the likelihood of a critical strike to the facility. The probability of a critical strike where detonator cables are exposed to electromagnetic fields is driven by the construction type, size and location of the facility, and by the frequency and density of lightning strikes.

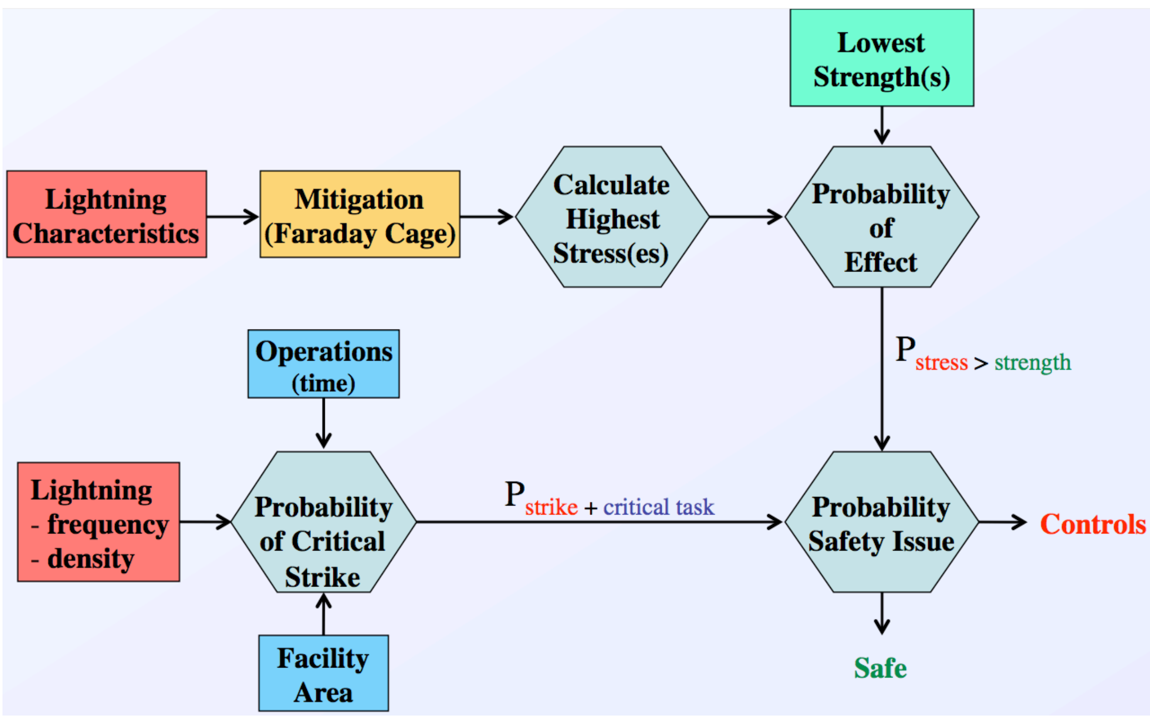

Figure 2.1. The safety assessment methodology has two parts, the comparison of stresses and strengths and the likelihood of a critical strike.

The ultimate goal of an assessment is to determine the probability of an explosion and, if needed, recommend safety controls. However, it is very time consuming to accurately compute the probability of a detonation as there are almost an infinite number of coupling configurations that produce the stresses. Instead, a few worst-case configurations are analyzed to produce the maximum stress levels along with an estimated probability of occurrence. The detonator strength data is usually obtained by testing a modest number of samples. The extrapolation from test data is reported as a minimum strength threshold with some likelihood of detonation below this level. It is the cumulative probability of detonation below the stated voltage, e.g., 10^{-3} if the stress is less than 5 kV. If this cumulative strength probability is multiplied by the cumulative stress probability above the stated voltage, the product gives a sense, though optimistic, of the overall odds of an inadvertent explosion given a lightning strike. Combining this with operational considerations produces an estimated likelihood of an HE mishap. While impractical most times, a mathematic approach using hypothetical data will be offered to clarify the theory.

Assessment Steps

HE detonation is a complex chain of electrical, plasma physics and chemical processes. At the start of the process, the detonator requires sufficient voltage, current and energy to operate. A bridge-wire detonator is normally initiated with a voltage pulse applied between the two conductors of a detonator cable, or in differential mode. For indirect lightning, RF energy extracted by a detonator cable generates much higher common-mode voltage to “ground” than the differential-mode voltage between the two conductors. A detonator can be initiated by applying the same high voltage (common-mode) to both conductors with respect to ground. The bridge-wire is normally isolated from electrical ground points by the insulating property of the explosive materials in and around the detonator. With sufficient voltage, an arc forms across the insulator surface allowing current from the connections to the bridge-wire to reach ground.

The common-mode voltage might start an arc, but the initiation of the explosive chain additionally requires sufficient electrical current and energy. Hence, the detonation analysis can be divided into three steps. (See Figure 2.2.) The indirect lightning hazard can be dismissed, or screened, if stress levels are exceptionally low at any of the steps. However, the recommended comparisons are prioritized to minimize effort. For example, it is more difficult to calculate energy than voltage stress. Voltage is needed to compute energy, therefore, the voltage needs to be calculated first. In some coupling situations, the voltage might be exceedingly low, and the assessment could stop at the first step. The second step focuses on current. Some detonators are sensitive to peak current as well as energy. Maximum current levels are easier to calculate than energy that requires knowledge of the dynamic arc resistance.

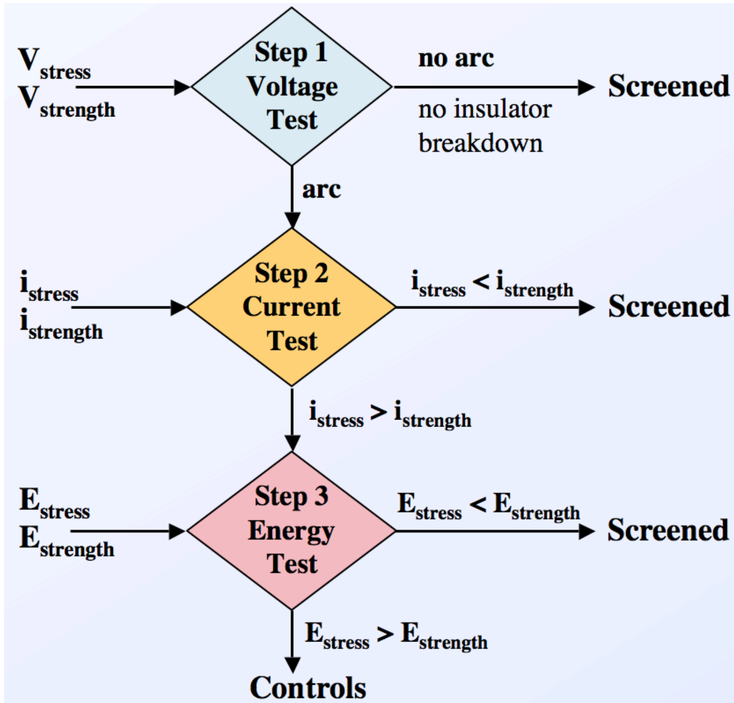

Figure 2.2. Evaluating the possibility of initiating a detonator has three steps.

Coupling Model

For this report an explosive object is defined as a metal container that encloses a large amount of HE and includes a detonator and cable. For safety reasons, it is assumed the cable is not yet attached to the electrical initiator.

Ideally, the explosive object would be available for low- and high-power coupling tests that relate known EM field level to voltages and currents measured at the detonator. High-power testing is very expensive, and for safety reason may not be allowed. Low-power coupling measurements are more practical. Even if the explosive object was available, it may be too large to fit into a transverse electromagnetic (TEM) transmission test cell [3] that can operate at the low and high frequencies associated with lightning currents. Scaled or partial models of the test object could be tested, but construction and testing create new problems. For example, there might be safety hazards associated with a detonator. Further, it is not feasible to replicate the actually work station with the TEM cell. Another assumption is the test object is physically too complicated for simple analytical coupling equations. Thus, a hybrid approach will be explained.

EM computer models can be developed to calculate stresses. Calculating the stress levels at a detonator for a configuration during the assembly or disassembly process is possible. However, these full-size high-resolution and dynamic electromagnetic computer simulations are complicated and expensive. Design drawings and assembly procedures must be studied to develop the models. (See Figure 2.3.) While a 3D computer simulation of time-varying EM fields interacting with a high-resolution coupling model could be developed, it is presently not practical nor needed. A more reasonable and equally effective hybrid approach has been developed which avoids these difficulties.

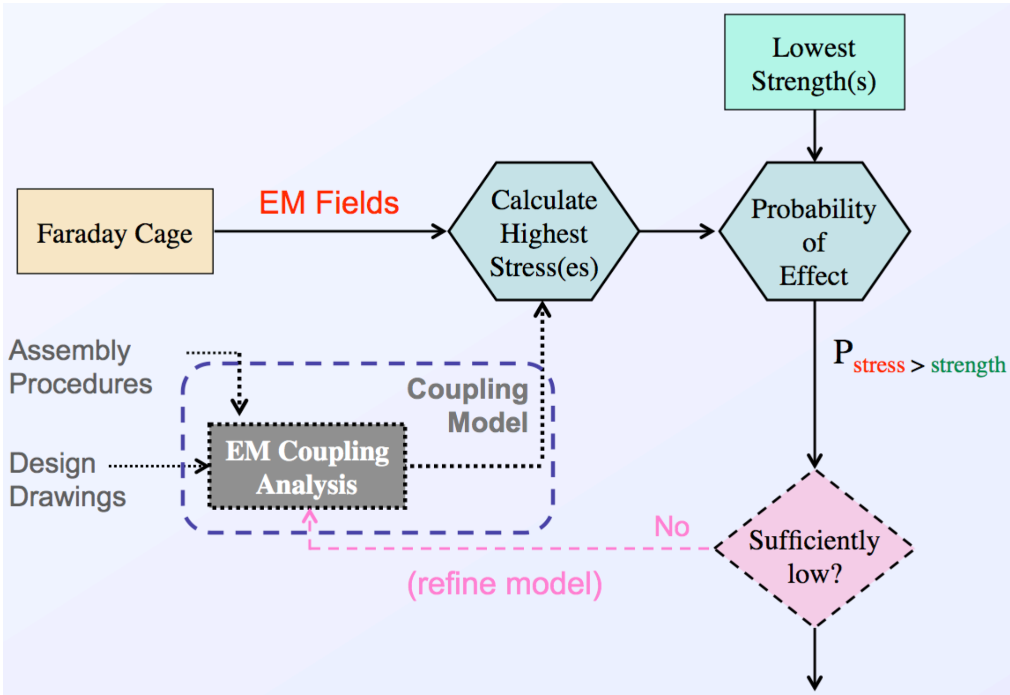

Figure 2.3. An EM coupling model must be developed to determine stress levels.

In the RF spectrum, lightning produces relatively low frequency signatures where the power spectral density above a few megahertz is extremely low. Therefore, the lightning current wavelength is very long when compared with the facility and detonator cable dimensions. The induced EM fields appear to change slowly, and allows us to use a combination of simpler equations, component-level quasi-static (without propagation delays) EM computer simulations and lumped-element circuit modeling to produce acceptable results more quickly. The development of the coupling model can be done iteratively. Starting with the simplest model that leaves out complex stress reducing details, a conservative probability of effect can be estimated. If there is sufficient safety margin between stress and strength levels, this worst-case analysis is adequate. If the probability of an initiation is not convincingly low, the model can be refined by reducing overly conservative assumptions by adding more details. This produces more accurate and lower stress levels by including stress-relieving features.

Without coupling tests on the explosive object, the circuit model, formulas, and EM modeling software must be validated before they are used in a crucial safety assessment. (If the object were available for testing, computer simulations could be validated against coupling test results.) The validation of the circuit model and circuit elements depends on cross-validation between low-power laboratory coupling studies, analytical equations and computer simulations of simple antenna systems. (See Figure 2.4.) Then the validated tools are applied to the far more complex test object. In the laboratory, well-characterized EM fields generated in a TEM cell [3] excite the small antennas connected by standard coaxial cables to known resistive loads. The measured stress levels must agree with results from equations and the circuit model. Validation of monopole-antenna coupling can be found in reference [4]. Each element in the circuit must also undergo the validation process. For example, a monopole antenna can be represented as a voltage source and series capacitor. Their values were calculated with first principle or empirical equations and compared against simple computer simulations and laboratory studies.

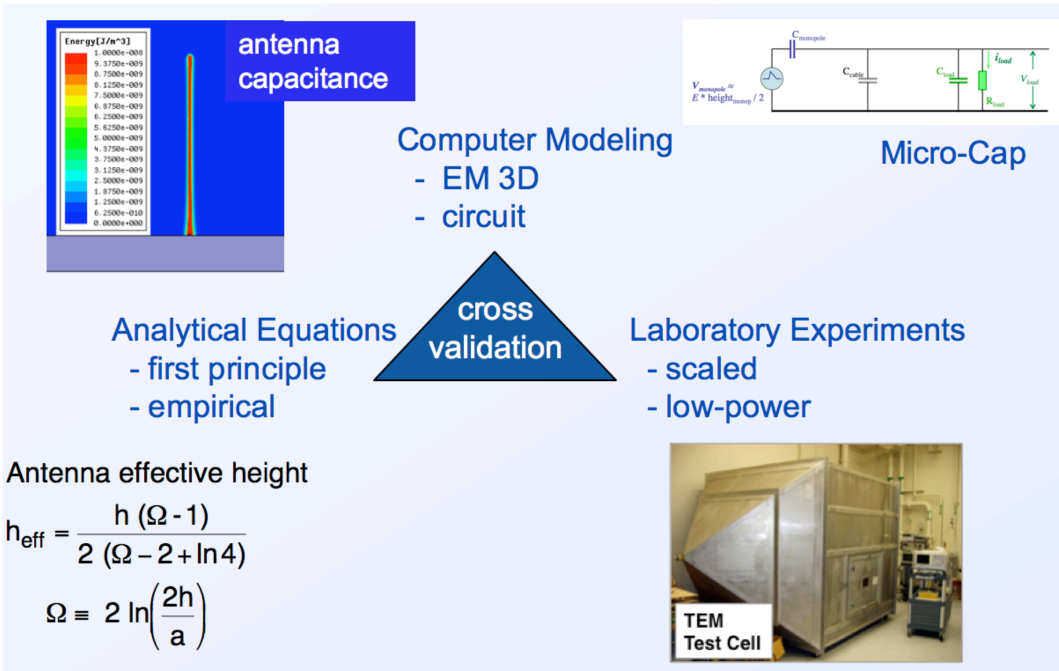

Figure 2.4. EM coupling models for safety assessments are cross validated.

Coupled Stresses

Stresses at the detonators are generated by the electric and magnetic field coupling onto the cables. The cables of interest are connected to the detonators. For simplicity, the cables can be modeled as either monopole or dipole, and loop type antennas. A detonator would normally be seated in the explosive object, and, if it has metallic components, it could become the lower arm of a dipole antenna. The linear antenna is excited by the electric field, and the loop is excited mainly by the change in magnetic field. A real cable could form a combination of the two types of antennas, but this would not produce the highest stresses. A summary of relative stress levels caused by the lightning induced fields interacting with the antenna types is given in Figure 2.5. It is assumed that the facility forms a poor Faraday cage that produces high electric fields because of high inductance. As a point of reference for RF engineers, the cell impedance is higher than the 377Ω of free space. For a given length of cable, the dipole configuration produces the higher voltages but relatively low current or energy levels. Contrastingly, an open loop generates lower voltages. However, if the loop formed a contiguous (closed) circuit, it has the potential to generate a larger amount of current or energy. The loop has the lower output impedance.

Step	Dipole	Loop	Note
1. Voltage	high	low	
2. Current	low	high*	* only if contiguous
3. Energy	low	high*	

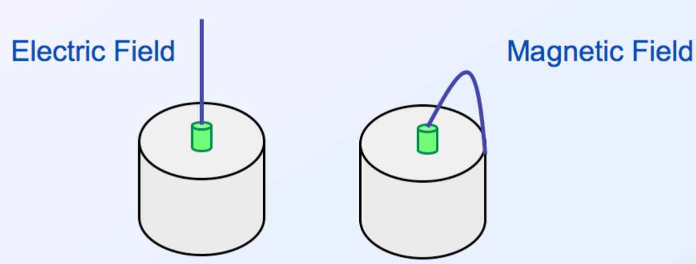

Figure 2.5. In a low quality Faraday cage, dipole antennas produce more voltage, and loops can generate higher current and energy levels.

A number of concepts have been presented: initiation steps, stress and strength comparisons, and antenna coupling levels. In the next section, these concepts will be applied to a simple hypothetical example.

3. Example

In this example, a very simple configuration will be evaluated. (It does not represent any real explosive object that is generally more complex.) Nonetheless, the object contains all of the major electrical features that are important in the analysis. Two of the three comparison steps, voltage and current, will be illustrated. Hypothetical stress and strength probability distributions will used to demonstrate the calculations necessary to determine the likelihood of an initiation. In our example, worst-case assumptions will be used to flush out the threat, and rough probability analysis will put the results in perspective.

The methodology specifies as a first step an evaluation for voltage breakdown. The voltage generated by a monopole or dipole is generally higher than by a loop given a cable length, so we will start the analysis with the linear antenna.

Linear Antennas

In this example, the explosives are assumed to be in a poor quality Faraday cage. In an actual assessment with many facilities, the worst facility would be evaluated first. If the HE object is safe in the worst building, it could then be put into any building. If the analysis indicates an insufficient safety margin, controls must be added that might include not using the worst facility. In this example the facility is hit by extremely powerful lightning [2]. This type of strike occurs less than 1% of the time. The peak current is 200 kA and maximum rise-rate is 400 kA/μs. Our poor quality Faraday cage has a transverse impedance of 0.25 μH. If the top of the facility is struck, the peak voltage from ceiling to floor will be 100 kV based on the following formula:

$$V_{peak} = L\frac{di}{dt} = 0.25\text{uH} \ \ 400 \text{ kA}/\mu\text{s} \ = \ 100 \text{ kV}$$

If the building is 10 meters tall, the average electric field inside is 10 kV/m and generally vertically orientated. The field levels actually vary within the building, and computer modeling or EM analysis is required to obtain the fields around the explosive object. For this example, the crude approximations of 10 kV/m will be used.

The explosive object is shown in Figure 3.1. The detonator is attached to a 1-meter cable aligned with the vertical electrical field. The explosive is in a metallic cylinder assumed to be 1-meter tall setting on concrete. The cable and cylinder form a 2-meter long dipole antenna with a detonator located at the center. The dipole open-circuit voltage, V_{dipole}, is equal to the effective height, $h_{effective}$, multiplied by the portion of the electric field, *E,* aligned with the antenna. The effective height is approximately the total length of the antenna divided by 2.

$$V_{dipole} = E \ h_{effective} \approx \frac{E \ \ \text{length}}{2}$$

Therefore, the worst-case open-circuit voltage is about 10 kV, which would concentrate in the detonator shown in the expanded figure. A possible breakdown path is shown with the red dotted line in Figure 3.1. The electrical field would force current through the bridge-wire into the arc in the detonator. The other conductor on the right would also add current to the arc formation but not to the bridge-wire. Either the bridge-wire current or arc energy could initiate a detonator. (With ample current the bridge-wire will turn into an electrical arc.) In the preliminary phase of the assessment, an expert would be consulted to determine if the dielectric strength in a detonator might be less than 10 kV. In this example, let's assume arcing does not normally occur at 10 kV, but has been observed at lower voltages in a few rare cases. Further analysis is required.

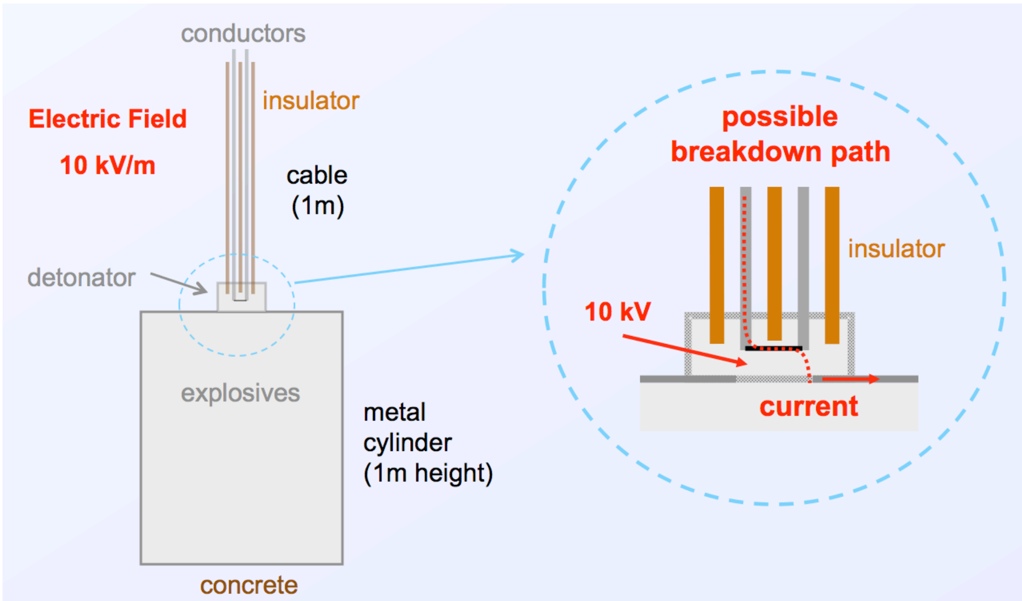

Figure 3.1. The hypothetical explosive object might form in arc in the detonator.

In this simplified analysis, a complex mechanism that reduces the detonator voltage was not considered. The 10 kV between the bridge-wire of the detonator and the metal cylinder would be reduced by a capacitive divider. It consists of the antenna capacitance, which is the exposed cable, and the capacitances of cable in the cylinder and detonator. However, if an arc is formed, these capacitors could also contribute additional current. The capacitive effect is very time consuming to quantify and will not be explained in this simplified analysis. The effect of this simplification and the resulting conservatism on the probability estimate will be covered in the next section.

This quick worst-case analysis indicates the lightning threat is a concern, but there is little information about the likelihood of arc formation. The next step is to estimate the probability of a voltage breakdown in the detonator given an extreme lightning strike to the facility. There will be a range of voltages appearing in the dipole, and the dielectric strength will also vary.

The voltage in the detonator is affected by the characteristics of three factors: (1) the lightning strike, (2) facility and (3) RF coupling. (1) The voltage is proportionate to the lightning current rise-rate. The distribution of rise-rates is reasonably understood [2]. (2) For a retrofitted facility, the shielding effectiveness varies due to construction type and the quality of the upgrade. Inside the building the electric and magnetic fields will vary between the strike point and location of the explosive object. (3) Finally, the RF coupling depends on the length and shape of the cable and cylinder, the orientation of these relative to the polarization of the fields, the shielding of the antenna by other metal components, and the previously mentioned capacitive divider. Therefore, the distribution of detonator voltages from a lightning strike is very complex and difficult to develop. For our simple example, a hypothetical distribution is given in Figure 3.2. (The x-axis is labeled "Voltage (kV-rel)" to reinforce the proposition that the plot is hypothetical.) The example is realistic to some extent but does not represent a particular HE object or facility. Each extreme lightning strike to some location on the worst facility with an exposed cable attached to explosive components would generate a point on the distribution plot. Clearly it is not possible to actually produce this type of plot by waiting for lightning strikes. Although a real distribution would have many more features, our hypothetical distribution still has the important trends. The distribution profile is log-normal. The mean voltage is much lower than 10 kV, and strikes producing voltages above 10 kV, though very rare, are not zero.

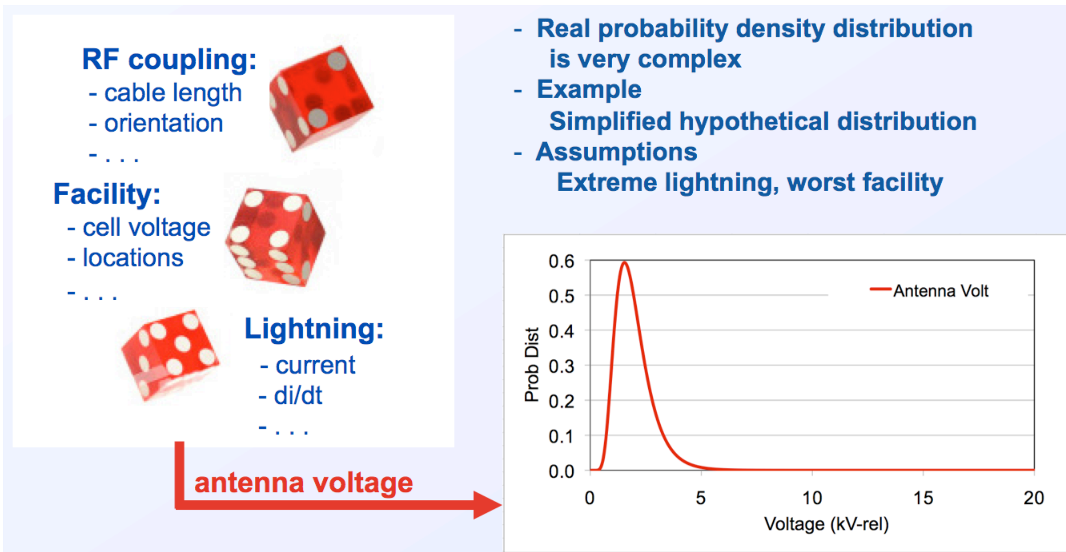

Figure 3.2. Antenna voltage varies because of differences in lightning current, facility shielding and RF coupling.

The breakdown voltage in a detonator is typically established by experiments. The instrumented detonators are subjected to high-voltage pulses. The average breakdown voltage can be reasonably found by testing a modest number of detonators. Finding the atypical weak units with defects with a variance of many sigmas from the mean is a nearly impossible task. Analysts usually fit the data to different types of distributions, such as log-normal, and use extrapolation to estimate the small number of weak detonators in a lot. This extrapolation must be applied cautiously because a manufacturing flaw in the next batch might lower the voltage strength of a detonator. Or there may be other types of defects, like faulty cable insulation, that could allow the formation of an arc at a lower voltage.

Hypothetical voltage stress and strength distributions are shown in Figure 3.3. To obtain the strength distribution, the detonators must be tested with a voltage pulse that is similar to the one supplied by the antenna. To match the dipole excitation, the detonator test pulse should be much shorter than the lightning current pulse. The dipole antenna voltage is related to the cell voltage, which depends on the derivative of the lightning current.

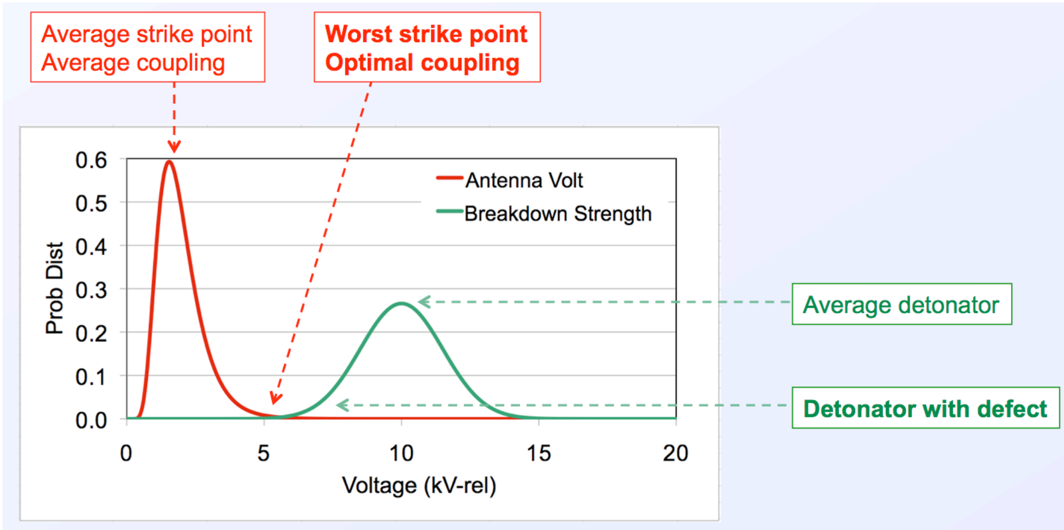

Figure 3.3. High-voltage stresses and weak detonators are rare events.

One simple interpretation of the stress and strength distribution is that the worst-case stress of 10 kV is so rare it might not cause any detonators to initiate, but this over simplification does not tell the right story.

The area of interest is in the overlap of the tails of the two distributions. The stress-strength plot is redrawn in the left plot in Figure 3.4 using a log scale for the probability density axis, and the overlap region is now visible. For a given stress voltage, an arc will form for all detonators that have a lower strength value. A point on the right plot in Figure 3.4 represents the probability of an arc formation given an extreme lightning strike ($Pr_{strike\text{->}arc}$) for a particular stress voltage (v). The point is calculated by multiplying the probability of producing the particular voltage (Pr_{stress}) and the mentioned cumulative probability of the detonator strength ($Pr_{strength}$) below the stress voltage.

$$Pr_{strike\text{->}arc}(v) \;=\; Pr_{stress}(V = v)\;\; Pr_{strength}(V < v)$$

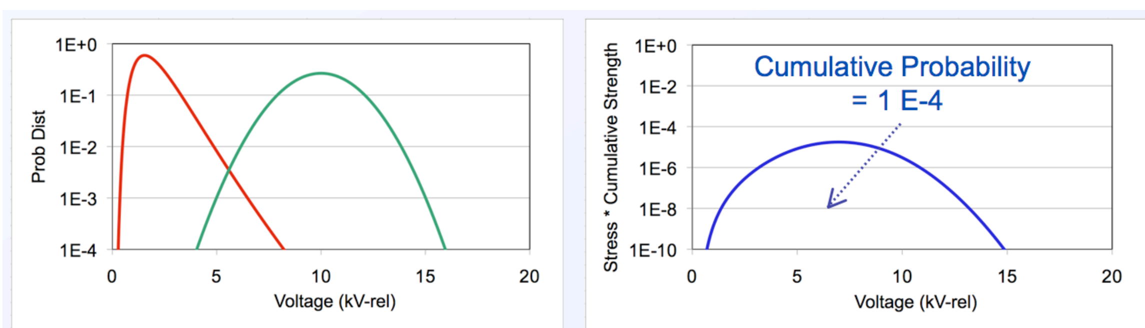

Figure 3.4. The likelihood of a high voltage pulse initiating a weak detonator is minute.

The area under the curve on the right plot shows the probability of voltage breakdown in a detonator given a strike.

$$Pr_{strike->arc} = \int Pr_{strike->arc}(v)\, dv$$

In this example, the probability of creating an arc is very low; about 10^{-4} or one voltage breakdown in ten thousand lightning strikes. This level of risk may be acceptable for some HE operations. However, HE operations that include nuclear materials require a larger safety margin. By itself a voltage breakdown in a detonator does not necessarily mean an initiation of the HE. The antenna must also deliver sufficient peak current and energy. The next step in the analysis is to compare the peak current levels delivered by the antenna, the stress, against the peak current required to activate the detonator.

The process for computing the probability of initiation from the current is the same as for determining the chances of a voltage breakdown. If an arc is formed in the detonator, the dipole will produce a range of peak currents. It depends on factors like exposed antenna length, shielding or shadowing of the fields, orientation, and capacitances. This second step assumes that there is peak current strength data or analysis. (For some detonators, only energy strength numbers exist.) Comparison of peak current (i_{peak}) is simpler than evaluating energy which adds a temporal dimension.

$$Pr_{arc->initiation}(i_{peak}) = Pr_{stress}(I_{peak} = i_{peak})\ Pr_{strenght}(I_{peak} < i_{peak})$$

$$Pr_{arc->initiation} = \int Pr_{arc->initiation}(i_{peak})\, di$$

Let's assume the typical stress current is relatively low when compared with the detonator strength so that the $Pr_{arc->initiation}$ is 10^{-3}. For example, high-current type initiators require high peak currents to function. Given a voltage breakdown, the antenna current might cause one in a thousand detonators to initiate.

The odds of an initiation given a strike, $Pr_{strike->initiation}$ are calculated by multiplying the probability of voltage breakdown with the probability of initiation by peak current. It is about 10^{-7} and will provide a sufficient safety margin when operational factors are included. For didactic purposes, the two probabilities are assumed to be independent, and in reality there is some correlation.

$$Pr_{stirke->initiation} = Pr_{stirke->arc}\ Pr_{arc->initiation}$$

In this example energy analysis is not needed. Only linear antennas have been evaluated. Loops can also generate voltage and current stresses.

Loop Antenna

Loop voltage is the product of permeability constant (μ_0), area (A), and the rate of change of the magnetic field (*dB/dt*). Let's assume a large segment of the loop is formed by the same 1-meter cable used in the dipole example. (See Figure 2.5.) The rate of change of the magnetic field is given as 2 kWb/m^2 s.

$$V_{loop} = \mu_0 A \frac{dB}{dt}$$

The open-circuit voltage is about 100 V. This is much lower than the 10 kV produced by the dipole. Hence, the probability of forming an arc at the detonator is exceedingly low. Compare the 100 V against the voltage strength plot denoted in green in the left plot in Figure 3.4. The 100 V is well below the minimal value of the probability scale.

In order for the loop to generate large amounts of current, both ends of the cable must complete the electrical circuit. This requires that an arc is formed in the detonator and the disconnected end of the cable is electrically connected to the metallic cylinder. Without the loose end of the cable making electrical contact, the loop antenna reverts to a linear antenna with an effective height shorter than the previously discussed dipole. The low loop voltage and the double insulators should not increase the probability of detonation.

A summary of the analysis for the example is shown in Table 3.1. Both types of antenna have an extremely low probability of detonating the HE. The dipole antenna would not generate enough current, and the loop would not produce sufficient voltage to cause an arc.

Step	Dipole	Loop	Note
1. Voltage	Low Probability	Extremely Low Pr	
2. Current	Extremely Low Pr	n.a.	
3. Energy			Not needed

Table 3.1. Both dipole and loop antennas have an extremely low probability of causing detonator initiation.

In the next section, the overall probability of a detonation will be examined.

4. Probabilistic Perceptive

In the previous example, the assumptions were made that a facility was struck by lightning and the HE objective had a detonator with an exposed cable. In this section, the overall probability of an unintentional detonation will be explored. Concepts will be presented along with quantitative estimates derived from the previous example. The probability numbers are typically not well quantified and are conservatively estimated by expert judgment. The statistical figures given in this example are fairly typical, but they do not represent any particular facility or detonator type.

Depending on storm patterns, and the location, size and height of a given structure and other nearby structures, the probability of a particular facility being struck varies greatly. If the reader is interested, reference [5] provides a sophisticated technique to estimate the number of strikes. Personnel at the facility can also estimate the number of lightning strikes to a plant, however they will likely under estimate the strike frequency because the buildings are not always occupied. The number of strikes to a facility over a year can be roughly calculated by multiplying the strike density, $D_{strike\,/\,year\text{-}area}$, by the effective area of the facility, $A_{facility}$. General strike density data (strikes / yr – km^2) for a region is available [5], and finer resolution data is available for purchase from commercial sources. Even if there are strikes within an area, not every strike will hit the building performing sensitive HE activities. Administrative buildings, tall light poles, and metal fences could also be struck. In our example, we will assume a 1 km^2 plant that is struck once a year. Our particular building is situated among many other structures; let's assume it is struck once every 100 years.

$$N_{facility-strikes/\,year} = D_{strike/\,year-area}\,\mathrm{A}_{\text{facility}}$$

Not every step in manufacturing, assembly or disassembly of an HE object is critical. For example, a detonator may not be placed in the HE, or the completely assembled HE object may be protected by a metal box that acts as a Faraday cage. The critical operations have the detonators in the HE and the cables exposed to the EM fields generated by a lightning strike. The combined probability that a facility is struck while performing a critical task is shown in Figure 4.1. For our example, we will assume that critical operations occur about 1% of the time over a period of a year. The rest of the time the facility could be idle, in maintenance mode, in preparation for the HE tasks, or performing non-crucial operations. We assumed duration of the critical step would be kept to a minimum. For example, detonator cables in the critical condition are not left exposed during the off work periods.

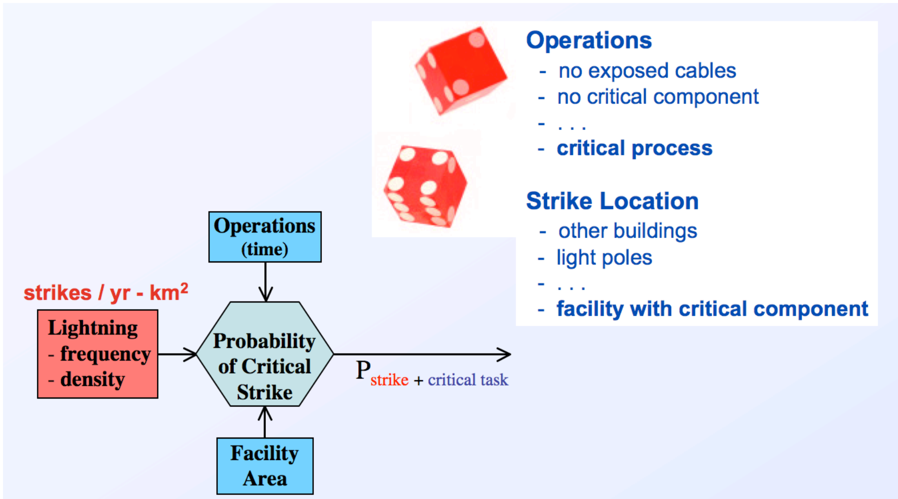

Figure 4.1. The probability of a facility being struck while performing a critical task is affected by many factors.

The overall probability of an explosion is determined by combining the result from the stress and strength calculation with probability of a strike during a critical task. (See Figure 4.2.) The probability levels are given as order-of-magnitude estimates. The case of the dipole coupling is shown. The blue number in the upper left corner, $<10^{-1}$, characterizes the probability of extreme lightning strike used our analyses. This number was separated out from the stress-strength arc formation calculation to emphasize that an extreme type of lightning was used in the calculation. Both the peak current level and the current rise rate are extreme, and this combination likely does not exist.

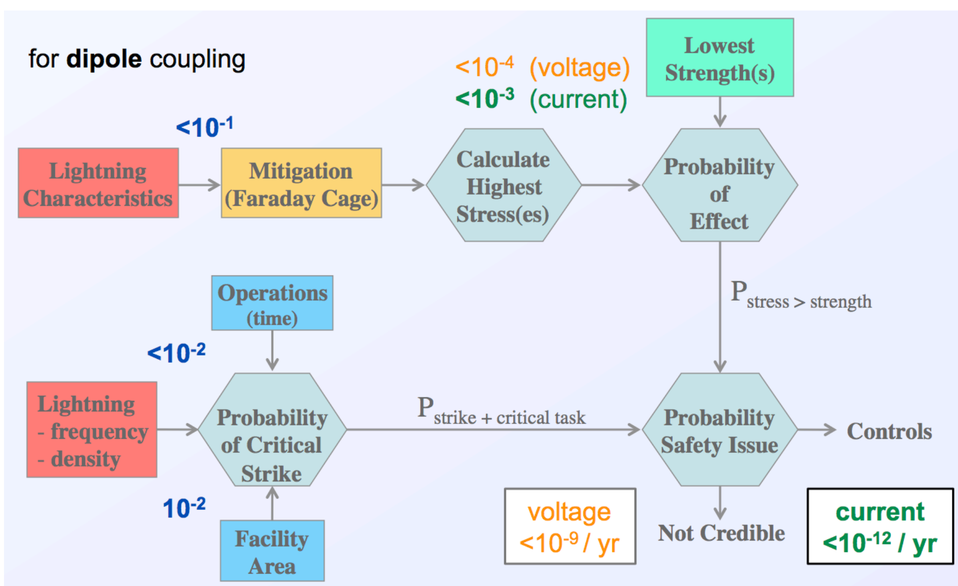

Figure 4.2. The probability of an explosion depends on the facility being struck during a critical operation and the resulting stress being greater than the strength.

The chance of voltage breakdown in a detonator is determined by combining the numbers in blue with the voltage breakdown probability in orange. Based on that calculation, insulator breakdown is a very rare event, possibly happening once in 10^9 years. When combined with the probability that the critical current level is also exceeded, the possibility of initiating a detonation is now one in 10^{12} years. If this number was not low enough, the energy calculation may indicate a larger safety margin. It is clearly difficult to validate such small probabilities.

The odds of an unintended explosion caused by loop coupling are shown in Figure 4.3. The loop antenna generates a much lower voltage than a dipole antenna. Hence, the probability of creating an arc in the detonator is extremely small; 10^{-8}. The strength levels at the low voltages were extrapolated from test data taken at much higher voltages. Our preference is to minimize extrapolations because of the possibility of unforeseen failure mechanisms. Unless the statistics are based on a very large data set representing all possible detonator conditions, using probability of failure numbers in the range of 10^{-2} to 10^{-3} is more realistic. The loop dielectric strength is actually determined by the breakdown level of two separate and different insulators. Hence, if each insulator had a failure rate of 10^{-4}, the 10^{-8} is closer to being acceptable. The probability of generating sufficient current for an initiation was not calculated because the voltage breakdown probability of 10^{-13} was adequately low.

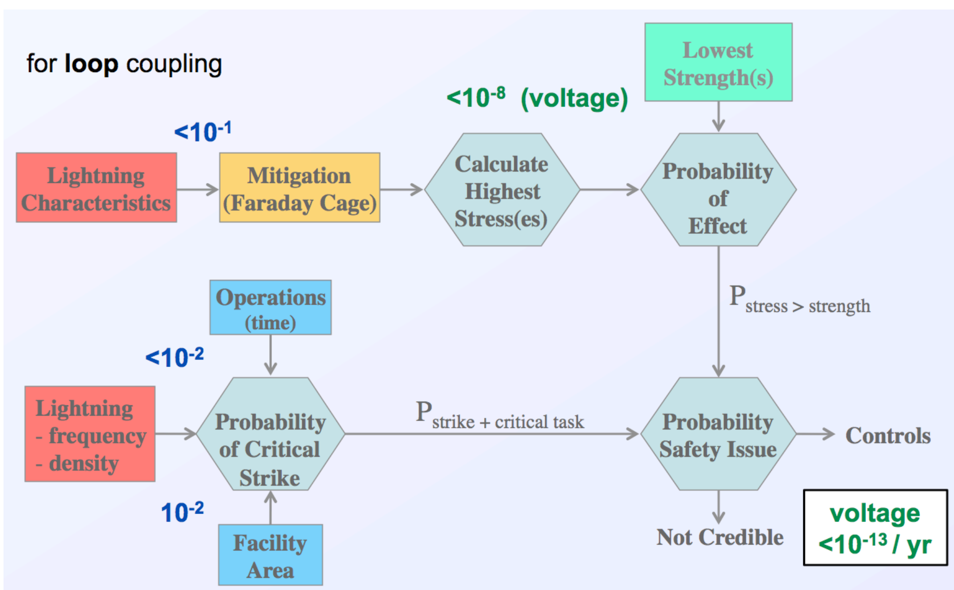

Figure 4.3. The probability of initiating a detonator is extremely small because the induced voltage stress is small.

5. Conclusions and Recommendations

Determining the probability of EM fields from a lightning strike causing an unintended HE detonation is involved and difficult. Based on our analysis, Faraday cages are reasonably effective at reducing electric fields so that more robust detonators are safe. The detonator failure mode starts with an arc formation. If there is sufficient current and energy, the explosive chain will start. While it is relatively easy to form a dipole antenna around a detonator, contiguous loop antennas do not naturally form. When the dipole is excited by the electric field, it can generate more voltage than a loop antenna excited by the magnetic field. However, the dipole current capacity is more limited. The typical loop antenna configurations are safe because they generate lower voltages. This greatly reduces the likelihood of the magnetic fields forcing large loop currents into a detonator.

This report describes the methodology of safety assessment without going into the details of how to determine antenna voltages, currents and energy; and probabilities. While the subject of RF coupling is complex, it has been well developed. There are many techniques for developing stress and strength probability estimates, including expert judgment, analytical calculations, computer modeling, scaled laboratory experiments, and full-scale testing. Their relative accuracy, the compensating conservatism, and costs are shown in Figure 5.1. In safety assessments, if the accuracy is known to be low or there is large uncertainty, conservatism is increased to compensate. Typically we have applied the first three techniques depending on risk, scheduling demands, and resources. Scaled experiments are possible, and full-scale lighting tests have been performed only once by Sandia National Laboratory. Depending on the consequence of an explosion and the perceived safety margin, the high cost of an accurate assessment is justified.

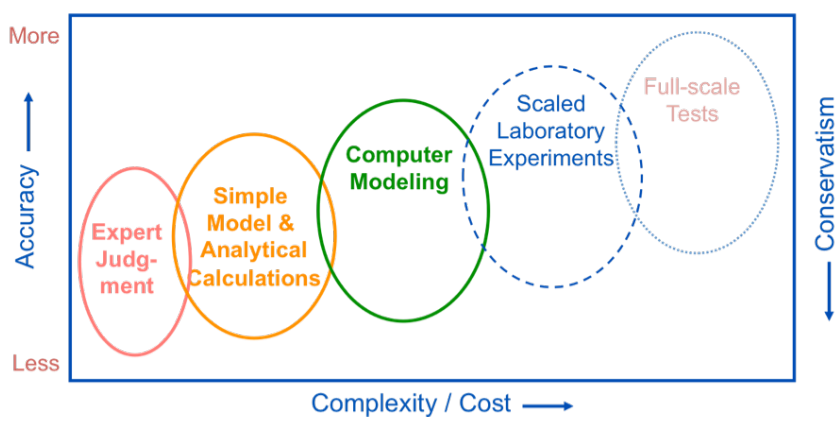

Figure 5.1. There are many options for quantifying EM coupling.

The HE operations can be adversely effected by nearby lighting strikes. The following four recommendations should mitigate the hazard. (1) Faraday cage type facilities are an important engineering safety barrier. The best ones incorporate Faraday cage modifications into the design and construction of the building. However, even an old rebar-reinforced concrete structure can be converted into Faraday cages. (2) The use of high-current detonators adds significantly to HE safety. The safety assessment for this type of detonator is relatively easy because the safety margins should be large and many simplifications to the analysis are possible. (3) The time period when the detonator is in the HE and the cables are exposed to possible lightning induced EM fields should be kept as short as possible. When the detonator is in the HE it can be protected from EM fields with a local Faraday cage. Sometimes this is simply the outside metal case with proper consideration of metallic penetrations. If the detonators must be left in a vulnerable configuration, a number of simple cable changes can reduce the risk. This includes minimizing effective antenna length and protecting the ends of the cable to prevent formation of a loop antenna. (4) The best solution is <u>not</u> to perform the risky operations during a thunderstorm. Lightning warning systems are reasonably reliable and, depending on the frequency of storms, this approach could have minimal impact on operations while improving safety.

Before implementing these recommended safety modifications, a general safety assessment should be completed so that managers understand the risk of indirect lightning induced detonation and can allocate the right amount of resources necessary to protect their facilities.

May lightning never strike your facility.

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The indirect-lightning safety assessment methodology is a variation of the one developed for the Department of Energy (DOE) and Department of Defense (DoD) to determine the vulnerability of military systems subjected to electromagnetic pulses (EMP) and high-power microwaves (HPM).

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