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Preliminary Lightning Hazard Study

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Preliminary Lightning Hazard Study

by

L. W. Miller

PRELIMINARY LIGHTNING HAZARD STUDY

by

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ABSTRACT

The probability of a lightning stroke to a simple but reasonable model for an underground nuclear test setup is calculated. The calculation is a rather crude approximation; however, its main point is to illustrate the more important mechanisms whereby lightning current can be introduced into the system and to indicate the steps that should be taken to do a more exact calculation. The consequences of such a lightning stroke are also calculated so far as possible. It is concluded that pulses of amplitudes in the range of a few hundred volts to 15 kilovolts can be induced across down-hole loads. The probability of a 15 kilovolt pulse is estimated to be about 2×10^{-6} per thunderstorm-day. Pulses of amplitude less than 1.5 kilovolts are more than 100 times as probable as this and thus constitute the main effect to be expected due to thunderstorms in the vicinity of an underground weapon testing operation.

This is a preliminary report of a theoretical investigation of the hazards presented by lightning during underground weapon testing activities. The problem considered is twofold; first, an estimate of the probability of a lightning stroke to a test installation is made and second, an effort to determine the effect of such an event is made. The type of installation considered is that in which the bomb is emplaced in a hole in the ground, or well, which is completely cased. The bomb and associated detectors also located in the well are connected to cables which emerge from the well and are run along the surface of the ground for some distance. This is an oversimplification of the total problem. There are, for example, lightning hazards during transportation of the bomb and during the process of lowering it into the well. However, it is hoped that the results obtained from the following considerations can be extrapolated to some extent to such other situations or that they will at least be useful in indicating a way to make the appropriate calculations.

Most lightning discharges are of the cloud-to-cloud type; however, the type of discharge of primary concern here is the cloud-to-ground type. A complete lightning discharge is called a flash and is made up of one or more partial discharges called strokes or return strokes, each of which is preceded by a leader. The first stroke is preceded by a stepped leader and subsequent strokes are preceded by either another stepped leader or by a dart leader. The leaders propagate from the cloud to the ground; they are electrically charged and conducting so as to carry the cloud potential down to the ground. They are relatively very weak processes compared to the return strokes which follow them. When electrical contact between the lower end of a leader and ground is established the conducting, charged leader is short-circuited and a current pulse propagates upward from the ground to the cloud. This current pulse constitutes the return stroke. Peak currents in return strokes average 10 to 20 kiloamperes. The current rises to its peak value in 1 to 10 μ sec. and has fallen to half value in about

40 μ sec; however, currents the order of hundreds of amperes may continue to flow for several milliseconds. After a time interval of a few milliseconds up to a few hundred milliseconds, the leader-return stroke process may be repeated one or more times. The time duration of the total discharge or flash is of order 0.2 sec. Nearly all flashes bring negative charge to the ground. Additional information on the characteristics of lightning can be found in references 1 and 2.

As indicated above the peak current in a stroke in an average flash is of order 15 kiloamperes. Flashes with peak currents of 150 kiloamperes or more constitute less than 1% of the total number of flashes. Thus, although the effect of an extremely high current lightning stroke might be predicted to be spectacular, such an event is extremely improbable compared to the probability of an average lightning stroke. Therefore, although the effects of both average strokes and large strokes will be discussed in this report, there will be somewhat more emphasis on average strokes.

If lightning strikes the ground the electric field near the point struck exceeds the breakdown field and enough ionization is produced to greatly increase the conductivity of the ground. If the breakdown field is E_0 and the highly conducting ionized region is taken to be a hemisphere of radius r_0 then for distances r greater than r_0 from the point struck the electric field is less than E_0 and satisfies the relation $\vec{J} \approx \sigma \vec{E}$ where σ is the conductivity of the normal, unionized earth. If the current is uniform over a hemispherical surface the current density $\vec{J}$ is equal to $I/2\pi r^2$ where I is the current in the lightning stroke. Thus,

$$E = \frac{I}{2\pi\sigma r^2} = -\frac{\partial V}{\partial r}.$$

The potential at any distance r greater than r_0 is

$$V(r) = \frac{I}{2\pi\sigma r}.$$

The ratio $R_0 = V(r_0)/I$ is the resistance between the point struck and a remote point in the earth. If the expression $E_0 = I/2\pi\sigma r_0^2$ is solved for r_0

$$r_0 = \left(\frac{I}{2\pi\sigma E_0}\right)^{1/2}$$

and substituted into the expression for $V(r_0)/I$ then one obtains

$$R_0 = \left(\frac{E_0}{2\pi\sigma I}\right)^{1/2}$$

as the ground resistance of the point struck by lightning. Using the values

$$\begin{aligned} E_0 &= 10^5 \text{ to } 2 \times 10^6 \text{ V/m} & (\text{ref. 3, pg.267}) \\ \sigma &= 2 \times 10^{-2} \text{ to } 10^{-3} \text{ mho/m} & (\text{ref. 4, 5}) \\ I &= 1.5 \times 10^4 \text{ to } 1.5 \times 10^5 \text{ amp} & (\text{ref. 1}) \end{aligned}$$

one obtains

$$\begin{aligned} r_0 &\approx .25 \text{ to } 1.5 \text{ meters} \\ R_0 &\approx 2 \text{ to } 150 \text{ ohms} . \end{aligned}$$

The potential of the ground within a distance r_0 of the point struck is IR_0 . If, for example $I = 15$ kiloamperes and $R_0 = 10 \Omega$ then this potential is 1.5×10^5 volts. For distances $r > r_0$ the potential can be written

$$V(r) = IR_0 \frac{r_0}{r}.$$

Now suppose a long uninsulated conductor such as a wire or cable passes on or under the ground within a distance of a few times r_0 of the point struck. Clearly this long conductor will then carry a significant fraction of the lightning current which would otherwise have flowed in the ground. Thus, the conductor may be regarded in a sense as having been "struck by lightning". If the stroke is sufficiently close to the conductor it will arc to it; even if the stroke is several times r_0 from the conductor some current will still be induced in it by resistive coupling. The presence of the conductor will drastically alter the potential distribution given by the above equation because of this induced current if it is close to the point struck. However, this equation can be used to discuss in a crude sense the meaning of the distance which we will call d , from the cable within which the lightning stroke must occur in order for the conductor to be regarded as "struck by lightning".

If the cable were insulated but grounded at some remote point it might be convenient to define d

such that for strokes farther from the cable than d the insulation did not break down whereas it did for closer strokes. In other words d is defined by the equation

$$V_b = IR_0 \frac{r_0}{d}$$

where V_b is the breakdown potential of the insulation. Because of the large values that IR_0 is likely to have for a lightning stroke it is clear that a value of d so defined would be many times r_0 for ordinary types of insulation. On the other hand d might be defined such that for strokes closer than d the cable carries a major fraction of the lightning current, i.e., $d \approx 3 r_0$ for example. A value of d so defined is comparable to the distance a lightning stroke to the ground will arc to a buried conductor.³ Such a value of d is probably most useful for the purpose at hand but from the above discussion it should be clear that strokes to ground at distances from the cable greater than this d may induce a significant current in the cable.

In this connection it should be pointed out that a conductor lying on the ground will probably not attract lightning in the way that a lightning rod does. The reason for this is the fact that the average time interval between steps in a stepped leader is about 50 μ sec. The relaxation time c/σ for the cancellation of the field produced underground by a stepped leader is in general much less than this, so the potential of a grounded conductor will be very nearly the same as that of the earth nearby during the approach of a stepped leader. Thus, the conductor does not significantly perturb the field if it lies on the ground.

The probability that a cable is struck can now be calculated. Thus, if l is the length of the cable and the number of lightning flashes per unit area per thunderstorm-day is N then the probability per thunderstorm-day that the cable is struck is

$$P = 2Nd\lambda$$

From reference 3 pg. 296, $N = 0.1/\text{km}^2$ per thunderstorm-day, so if $l = 100$ meters and $d = 10$ meters, $P = 2 \times 10^{-4}$ per thunderstorm-day.

From the above discussion it is clear that d is a rather poorly defined quantity; its value really depends upon what is meant by the expression "struck by lightning" as well as on the electrical conductivity and breakdown field of the earth and the current in the stroke. This seems to be an unavoidable difficulty in the calculation of the probability of a lightning stroke to a cable on the ground.

We now consider the effect that a lightning stroke might have on an underground nuclear weapon test setup. In order to do this a configuration for the electrical connections will be assumed in which certain easy steps have been taken to reduce the danger of lightning damage but which represents only a minor modification of configurations actually used. A bundle of shielded cables is assumed to run a distance the order of 100 meters along the surface of the ground from the top of the hole (well-head) in which the nuclear device is emplaced to a data recording station. Each of the cables may contain one or more conductors, which may or may not be coaxial, inside of its shield or outer conductor. The shields of all of the cables are grounded to the well casing at the well-head and are bonded together at intervals along their length. The resistance of the shields running in parallel from the data recording station to the well-head is taken to be less than 0.1 ohm. If necessary, a sufficiently large piece of copper wire can be run in parallel with and bonded to the outer conductors of the cables to achieve this low a resistance. There may be other bundles of cables running off in other directions from the well-head; if so, they are assumed to be connected in the same way. If there is a tower erected over the hole or a crane supporting the bomb then it is assumed to be grounded to the well casing. All conductors, such as wire ropes, supporting the bomb or plumbing that goes down the hole are assumed to be grounded to the hole casing at the well-head. The cable shields may also be connected to the earth at other points such as a specially constructed ground connection near the data recording stations or red shack.

We now assume that lightning strikes the cables somewhere between the well-head and the data recording station. If the tower is struck it is equivalent to the cables being struck near the well-head since both the cables and the tower are connected to

the well casing there. The lightning current will follow various paths to ground, most of the current flowing in the path of lowest impedance. The most obvious path to ground is by way of the well casing. The current will flow outward from the well casing into the ground with current density $\vec{J} = \sigma \vec{E}$ where σ is the earth conductivity and $\vec{E} = -\nabla V$ is the electric field and V is the potential in the earth surrounding the well casing. The well casing will be an equipotential surface of V and the ratio of the well casing potential to the current that it conducts to ground is the ground resistance of the well casing. An approximate expression for this resistance, i.e., the ground resistance of a cylinder of length l and radius a is³

$$R_g = \frac{\rho}{2\pi l} \ln \frac{l}{a}$$

where $\rho = 1/\sigma$ is the resistivity of the ground. Typical values of ρ are 50 to 1,000 ohm-meters so if $l \approx 100$ meters and $a \approx 1$ meter R_g could be as much as 7 ohms but values less than 1 ohm are more likely since l is usually much more than 100 meters.

Some of the lightning current might flow to ground at some other point at which the cable sheaths are intentionally grounded. Suppose such a ground connection is made by driving an array of interconnected copper rods into the ground and then chemically treating the soil in which they are driven so as to make it highly conducting. Such a connection would at best be equivalent to a connection consisting of a conducting hemisphere with the curved surface downward in contact with the earth and the flat surface at ground level.³ For a hemisphere of radius r the resistance of such a connection is³

$$R_g = \frac{\rho}{2\pi r}$$

If r is taken to be the radius of the array of conducting rods it is seen by comparison with the previous equation that this ground connection is in general not nearly as good as that due to the well casing unless the circumference of the array is comparable to the well depth. We will assume that the array is not that extensive, and neglect the current

flowing in this ground connection compared to that flowing to ground by way of the well casing.

There is also the possibility that some of the lightning current may be introduced into the power lines or telephone lines by way of an arc or short-circuit and thereby flow to ground at some ground connection located many kilometers from the point struck. Because of the distance to the ground connection the current will flow into the line for a period of time which is long compared to the rise time of a lightning stroke before any current flows to ground at the far end of the line.

Suppose a time dependent voltage $V(t)$ is applied to the input end of a transmission line. Then the charge on the line at time t must be given by an expression of the form

$$q(t) = \int_{-\infty}^{\infty} dt' S(t-t') V(t')$$

where the function $S(t-t')$ is zero for $t' > t$ and is independent of $V(t')$. This merely expresses the fact that $q(t)$ is a linear function of the voltage applied to the line at all times earlier than t . If $V(t')$ is a step function, i.e., $V(t') = 0$ for $t' < 0$ and $V(t') = V_0$ for $t' > 0$ then

$$q(t) = V_0 \int_0^t dt' S(t-t')$$

The coefficient of V_0 on the right hand side of this equation is simply the capacitance of the length of the transmission line that can be charged up by a step function voltage in time t . This length can be written as vt where v is the average propagation velocity and the capacitance can be written Cvt where C is the average capacitance per unit length. Both v and C are averages only over the length of the line that is charged up and are therefore in general time dependent quantities unless the line is uniform along its length. However, v is always less than the velocity of light and, from consideration of the probable dimensions and construction of the transmission line, it is reasonable to argue that C is less than or equal to the capacitance per unit length of ordinary coax cable or about 10^{-12} farad/cm. Thus, the characteristic impedance of the line $z = 1/Cv$ is always more than a few tens of ohms and probably more than

several hundred ohms and the above expression for $q(t)$, the charge on the line resulting from a step function voltage applied for a time t , can thus be written

$$q(t) = \frac{t}{2} V_0 .$$

Now, a power line or telephone line plus its electrical image in the ground can be regarded as a two-wire transmission line and the voltage pulse which might be applied due to a lightning stroke that arcs to such a line could be made up of a series of positive and negative step functions. From the above discussion, it should be clear that no matter how peculiar the electrical properties of such a transmission line might be, its characteristic impedance must be more than a few tens of ohms and therefore the current which flows in it must be negligible compared to that which flows to ground by way of the well casing if the line is sufficiently long. Since the average lightning stroke current falls to half value in 40 μ sec the line should be longer than 12 km for this argument to hold for the duration of this part of the current pulse.

In summary, three possible paths to ground for the lightning current have been considered.

- a) The well casing.
- b) Some specially prepared ground connection consisting of an array of conducting rods driven into chemically treated earth near the data recording station or red shack.
- c) A remote ground to which the test setup is connected by power lines or telephone lines.

Of these three only the well-casing ground seems to be important since in general the other two have at least an order of magnitude more impedance. Thus, a lightning stroke either directly to the cables or to the ground or to a building or to any other object near the cables will result in a major fraction of the lightning current flowing down the cable sheaths to the well casing and from there into the earth.

The current flowing in the cable sheaths results in an IR voltage drop along the sheath which is coupled into the inner conductor of the cable. One mode of coupling would be by way of an arc through the cable insulation. Another mode is the capacitive coupling between the inner and outer conductors

of the cable. Still another mode is by way of the device connected to the end of the cable in the data recording station; this might also involve an arc or breakdown of insulation. The actual coupling mechanism is in general a combination of the above modes in parallel and can be represented by an impedance Z_c which is not readily calculable except in special cases. Thus, if R_g is the resistance of the cable sheath between the point struck and the well-head, which we have assumed to be less than 0.1 ohm, R_g is the ground resistance of the well casing and Z_L is the impedance connected across the cable on the down-hole end; an equivalent circuit for the system is shown in Figure 1.

Fig. 1. Equivalent circuit showing the way a high voltage pulse is produced across Z_L , the load on the down-hole end of a cable. See the text for definitions of Z_c , R_s , and R_g .

For a high current lightning stroke with a current of 1.5×10^5 amp directly to the cables or within arcing distance of them the voltage across R_g would be 1.5×10^4 Volts (if R_g had its maximum value of 0.1 ohm) and the cable insulation could be expected to break down so Z_c would be small. Thus, the full 1.5×10^4 Volts would appear across Z_L . The probability of this occurring is about 1% of the probability of any lightning stroke to the

cables or about 2×10^{-6} per thunderstorm-day for a 100 meter cable. For an average lightning stroke within arcing distance of the cables the voltage across R_g would be 1.5×10^3 volts and there might not be any breakdown of insulation. Thus, the coupling impedance could be larger in this case and somewhat less than 1.5 KV would be induced across Z_L . The probability of this, as calculated above, is about 2×10^{-6} per thunderstorm-day. The probability of voltage pulses across Z_L of only a few hundred volts caused by average lightning strokes farther from the cables or by smaller strokes is significantly greater than this. Thus, from the standpoint of probability of occurrence this type of event represents by far the greatest hazard.

The purpose of the above discussion is to demonstrate the mechanism whereby lightning could introduce a high voltage pulse onto electrical wiring running to the vicinity of a bomb emplaced in a cased hole and to show that it would be a very difficult matter to completely eliminate the introduction of such a pulse. If there are coax cables lying on the ground then a nearby lightning stroke will induce very large currents to flow in their outer conductors. The resulting voltage drop along the cables will be coupled to the inner conductors even though the outer conductors are grounded to the well casing at the well head. The situation could be improved by reducing the resistance of the cable sheaths and providing spark gaps (lightning arrestors) across the cables at the well head. These measures are comparable to those customarily taken to protect underground power lines or telephone lines.³ By such means the probability of lightning damage to such systems can be greatly reduced but not completely eliminated.

The calculation so far has been based on the assumption that everything above ground that is likely to be struck by lightning is connected to the well casing which is by far the best ground available. Because of this it is possible to predict the path on which most of the current will flow. Moreover, the magnitude of the voltage pulse that is introduced down-hole can be calculated, at least approximately, as a function of the current in the

lightning stroke. For all except very high current lightning strokes the magnitude of this voltage pulse is small enough to permit the control of down-hole damage by means of improved insulation. If there are devices located in the well that are intended to operate on 10 to 20 volts then a pulse of 1,000 volts due to a lightning stroke would probably damage them; however, it is possible, at least in principle, to modify existing firing systems in such a way that a 15 KV pulse with a time dependence comparable to that of a lightning stroke will not detonate the bomb. The modification in question is primarily a matter of improving insulation so that arcing does not occur in critical circuits. Some calculations relating to this question are presented in Appendix 2 below.

If cables leading down-hole do not have their outer conductors grounded at the well-head then a lightning stroke would probably result in extensive arcing in down-hole circuits. The potentials of such cables will depend on the ratio of the impedances of these arcs and of the lightning channel between cloud and ground. Since this ratio is not known, the potential of the cables cannot be calculated. Very little can be said about it other than that it must be small compared to the cloud potential which is of order 10^8 volts.¹ Thus, in this case some uncalculable fraction of the total voltage and current in the lightning stroke would be introduced to the well. To protect the device against such an unknown high voltage pulse would be much more difficult than protecting it against the 15 KV or less pulse that would be introduced down-hole if the outer conductors of the cables are grounded.

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APPENDIX 1

DIFFERENCE BETWEEN CASED AND UNCASD HOLES

An approximate expression for the ground resistance of a cased hole which was used above is

$$R_g \approx \frac{\rho}{2\pi l} \ln \frac{l}{a}$$

where ρ is the resistivity of the ground, l is the depth of the hole and a is its radius. With an uncased hole the cables leading down to the bomb are in direct contact with the earth and the ground connection will be made by their outer conductors (which are assumed to be uninsulated). From Sunde³, pg 77, the combined ground resistance of n equal conductors of radius b arranged with equal spacing on a circle of diameter D small compared to their length may be computed by replacing a in the above formula with

$$a' = \left[nb \left(\frac{D}{2} \right)^{n-1} \right]^{1/n} = \left(\frac{2nb}{D} \right)^{1/n} \frac{D}{2}$$

However

$$\ln \frac{l}{a'} = \ln \frac{2l}{D} + \frac{1}{n} \ln \frac{D}{2nb}$$

If $n \approx 10$ and $D/2nb \approx 10$ then $\frac{1}{n} \ln \frac{D}{2nb} \approx 0.2$ and, if $\frac{D}{2} = a$, clearly R_g will not be significantly changed by this substitution.

Another difference between cased and uncased holes arises from the fact that for a cased hole most of the lightning current would flow down the casing, which would be expected to have a low resistance from end to end, probably much less than 0.1 ohm. With an uncased hole the lightning current would flow down the cables and this would result in a voltage drop along the outer conductors equal to the average current along the cables times their resistance which could be significantly greater than that of the hole casing. However, this voltage drop could be reduced by running a conductor of low resistance in parallel with the down-hole cables and bonding them to it at frequent intervals. The voltage drop along the outer conductors of the down-hole cables would be coupled to the inner conductors by the same mechanisms that perform this coupling for the above-ground portions of the cables.

APPENDIX 2

WAYS OF INTRODUCING LIGHTNING CURRENT INTO DETONATORS

There are three ways that detonators could be fired without any failure of the insulation within the firing unit. (The firing unit in question is the TC-133.) The most obvious way is for the lightning current to enter by the path on which the normal firing current enters, i.e., the current charges the 7 μ f capacitor connected across the spark gap to a high enough voltage to fire the gap. This capacitor is charged through a 50-ohm resistor which, if its insulation does not fail, implies a 350 μ sec time constant for charging the capacitor. Thus, if a lightning stroke could produce a step function voltage V lasting for 100 μ sec then the voltage across the capacitor would reach $(1 - e^{-100/350})V = 0.25 V$. If V were 15 KV then the voltage across the capacitor would reach 3.75 KV which would probably not fire the gap unless a trigger was supplied. However, a voltage of 15 KV would possibly break down the insulation of the 50 ohm resistor and therefore charge the capacitor in a shorter time or else break down the coax cable insulation and not charge it at all. The inductance of this capacitor is specified to be less than 3×10^{-8} henrys. Thus, if the lightning current has a rise time $1/\omega \approx 10^{-8}$ sec, then the impedance of this inductance would be $\omega L = .03$ ohm which is negligible.

If the cable by which this capacitor is charged extended beyond the well-head over the surface of the ground for some distance then a lightning stroke would cause a voltage on its center conductor in the way already discussed for such cables. Because of the nature of lightning flashes it is apparent that the most probable way of charging this capacitor would be by a multistroke flash with the strokes closely enough spaced in time or with a single stroke of sufficiently long time duration to produce an average of 4 KV on the center conductor of the cable for more than 350 μ sec. This would require an unusual type of lightning stroke. Moreover, this cable is ordinarily terminated at the well-head so the introduction of a high voltage to its center conductor would involve arcing from some other cable which is exposed to lightning above ground. Thus, this mode of introducing lightning current into the detonators seems highly improbable.

Another mode of introducing lightning current into detonators is to induce a voltage across the detonator by means of direct capacitative coupling between the detonator and some nearby point at a high voltage V . If the effective angular frequency of the lightning current is ω , the coupling capacitance is C , and the resistive load presented by the detonators is R , then the magnitude of the voltage across R can easily be shown to be $\omega RC V$ if $\omega RC \ll 1$. If V is 15 KV then the voltage across the detonators is 1.5 V if $\omega RC = 10^{-4}$. With $\omega = 10^6 \text{ sec}^{-1}$ this implies that $RC = 10^{-10} \text{ sec}$. It seems likely that the actual value of RC is much less than this. R is the resistance of all of the detonators connected in parallel and is therefore much less than an ohm while C represents whatever stray capacitative coupling there may be to nearby points on which a high voltage could be produced by lightning.

The third way that detonators could receive lightning energy without failure of insulation is by means of inductive coupling. The closed circuit consisting of the path from ground through a detonator to the load ring and back to ground by way of another detonator may be regarded as the secondary circuit of a transformer. If the mutual inductance of the transformer is M and the impedance of the secondary circuit is Z_2 , then the current induced in the secondary is $I_2 = \frac{1}{Z_2} M \frac{dI_1}{dt}$ where I_1 is the current in the primary circuit of the transformer. The primary circuit may be taken to be the segment of the center conductor of a coax cable between the point where it is struck by lightning and the place where the current that is caused to flow in it returns to the outer conductor or to ground by means of some device (also considered part of the primary circuit) to which the cable is connected at the bottom of the hole. If the impedance of the primary circuit is Z_1 then $I_1 = \frac{V_1}{Z_1}$ where V_1 is the voltage induced on the center conductor of a coax cable that is struck by lightning in the way already described. The impedance Z_1 must be at least equal

to the resistance of the center conductor of the cable which would be the order of 1 ohm if the total length of cable is 300 meters. Thus, $I_1 < \frac{V_1}{R_1}$ where $R_1 \approx 1 \text{ ohm}$. The voltage across the two detonators of total resistance R_2 is thus

$$V_2 = I_2 R_2 = \frac{R_2}{Z_2} M \frac{dI_1}{dt} < \frac{R_2}{Z_2} M \frac{1}{R_1} \frac{dV_1}{dt}$$

Since $Z_2 > R_2$ it follows that

$$V_2 < \frac{M}{R_1} \frac{dV_1}{dt} \approx \frac{\omega M}{R_1} V_1$$

If V_2 is to be 1.5 V when $V_1 = 15 \text{ KV}$ then $\omega M/R_1$ must be 10^{-4} . If $R_1 = 1 \text{ ohm}$, $\omega = 10^6 \text{ sec}^{-1}$ then this implies that $M = 10^{-10} \text{ henry}$. This is equal to the mutual inductance between an infinitely long straight wire and a loop of wire, lying in the same plane, at a distance of 1 meter from the long straight wire if the area of the loop is 5 cm^2 .

It appears that inductive coupling is a somewhat more likely way of introducing energy from a lightning stroke into detonators than either of the other two ways just discussed. However, by careful shielding of the detonator wiring the inductive coupling to other circuits could probably be reduced to a safe value without much difficulty. If this were done then it would be reasonable to argue that there is negligible probability of lightning detonating a bomb unless there is a break down of the insulation within the firing circuit. The probability of such a break down can be reduced by improving the insulation in the firing circuit and by taking steps to reduce the voltage that a lightning stroke could induce on the center conductors of coax cables leading down-hole. Such steps could include reducing the resistance along the outer conductors of the cables and installing spark gaps between inner and outer conductors at the well-head.