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Update Direct-Strike Lightning Environment for Stockpile-to-Target Sequence

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Auspices
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Final Report
To
Lawrence Livermore National Laboratory
From the
University of Florida
Department of Electrical and Computer Engineering
Principal Investigator: Martin A. Uman
by
M. A. Uman, V. A. Rakov, J. O. Elisme, D. M. Jordan, C. J. Biagi, and J. D. Hill

Executive Summary

The University of Florida has surveyed all relevant publications reporting lightning characteristics and presents here an up-to-date version of the direct-strike lightning environment specifications for nuclear weapons published in 1989 by R. J. Fisher and M. A. Uman. Further, we present functional expressions for current vs. time, current derivative vs. time, second current derivative vs. time, charge transfer vs. time, and action integral (specific energy) vs. time for first return strokes, for subsequent return strokes, and for continuing currents; and we give sets of constants for these expressions so that they yield approximately the median and extreme negative lightning parameters presented in this report. Expressions for the median negative lightning waveforms are plotted. Finally, we provide information on direct-strike lightning damage to metals such as stainless steel, which could be used as components of storage containers for nuclear waste materials; and we describe UF's new experimental research program to add to the sparse data base on the properties of positive lightning. Our literature survey, referred to above, is included in four Appendices.

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I. Introduction

The most recent lightning direct-strike environment specification for nuclear weapons was published 19 years ago by R. J. Fisher of the Sandia Corporation and Martin A. Uman of the University of Florida in the document "Recommended Baseline Direct-Strike Lightning Environment for Stockpile-to-Target Sequences", May 1989, SAND-89-0192, Sandia National Laboratories, Albuquerque, NM. New information about lightning has been made available in the last 19 years via measurements and analysis. As part of the present LLNL grant, the University of Florida has surveyed all relevant publications reporting lightning characteristics and presents here an up-to-date version of the 1989 direct-strike specifications. Information from UF's on-going program of measurement of the electromagnetic properties of close lightning, including the currents in triggered lightning strokes and the charge transfer in natural positive lightning, is, where appropriate, used to inform our judgments relative to the new specifications. Further, we present functional expressions for current vs. time, current derivative vs. time, second current derivative vs. time, charge transfer vs. time, and action integral (specific energy) vs. time for first return strokes, for subsequent return strokes, and for continuing currents; and we give sets of constants for these expressions so that they yield approximately the median and extreme negative lightning parameters presented in this report. Expressions for the median negative lightning waveforms are plotted. Finally, we provide information on direct-strike lightning damage to metals such as stainless steel, which could be used as components of storage containers for nuclear waste materials; and we describe UF's new experimental research program to add to the sparse data base on the properties of positive lightning.

The following four sections (II, III, IV, and V) of this final report deal with related aspects of the research: Section II. Recommended Direct-Strike Median and Extreme Parameters; Section III. Time-Domain Waveforms for First Strokes, Subsequent Strokes, and Continuing Currents; Section IV. Damage to Metal Surfaces by Lightning Currents; and Section V. Measurement of the Characteristics of Positive Lightning. Results of the literature search used to derive the material in Section II and Section IV are found in the Appendices: Appendix 1. Return Stroke Current, Appendix 2. Continuing Current, Appendix 3. Positive Lightning, and Appendix 4. Lightning Damage to Metal Surfaces.

II. Recommended Direct-Strike Median and Extreme Parameters.

An exact transcription of the direct-strike parameters recommended by Fisher and Uman (1989) (their Table 2) as the lightning environment to be used for stockpile-to-target sequences (STSs) for nuclear weapons is reproduced in Table 1. Fisher and Uman (1989) presented median (50%) values and extreme values (stated as "1% frequency of occurrence", but actually meaning 1% of all events are expected exceed that value) for the parameters listed, and they noted that knowledge of the form of the probability distribution function along with these two values is sufficient to define the full distribution. They also note that 1% values should not be considered absolute extremes.

The probability distribution functions of some lightning parameters have been shown from measured data to be approximately log-normal (Uman, 1987, Appendix B3, pg. 339). Six important lightning parameters that have been demonstrated to follow the log-normal distribution to a reasonable degree of approximation are the negative first and subsequent return stroke peak currents, the charge transfer to 1 msec for negative first and subsequent return stroke currents, positive first return stroke peak current, and the time interval between negative strokes. Cianos and Pierce (1972), in a table reproduced in Uman (1987, Appendix B3), list 10 lightning parameters that they suggest can be described satisfactory by a log-normal distribution: flash duration, interstroke interval, return stroke peak current, flash charge transfer, time to return stroke current peak, rate of rise of return stroke current, time to return stroke current half-value, duration of continuing current, continuing current amplitude, and continuing current charge. Nevertheless, some of these parameters are only crudely approximated by the log-normal distribution and are certainly not described satisfactory enough by that distribution to allow adequate prediction of extreme values.

Table 2 contains our present recommendations for parameters comprising the direct-strike environment. Negative and positive strokes, negative and positive continuing currents, and negative and positive flashes are treated separately, in contrast to Fisher and Uman (1989) who combined parameters for negative and positive events.

Table 1
Recommended Direct-Strike Lightning Environment for Future STSs.
Reproduced from Fisher and Uman (1989)

ABNORMAL LIGHTNING ENVIRONMENTS

A lightning strike directly to the warhead or to equipment associated with the warhead is considered a credible possibility. The lightning could be of either the cloud-to-ground or cloud flash (intracloud, intercloud, or cloud-to-air) type. Extreme (1% frequency of occurrence) and median (50%) values are given below for those cloud-to-ground flash parameters considered to constitute the most important threats to the weapon. Corresponding cloud flash parameters fall within the envelope defined below and are therefore not separately listed.

RETURN STROKE PARAMETERS[1]	1%	50%
a. Peak Current (kA)	200	30
b.Time to Peak (μs)	0.1-15	3
c. Max. Rate of Current Rise (kA/μs)	400	150
d.Time to Decay to Half Peak (μs)	10-500	50
e. Amplitude of Continuing Current[2] (A)	30-700	150
f. Duration of Continuing Current (ms)	500	150

FLASH PARAMETERS		
a. Number of Strokes	>20	4
b. Interstroke Interval (ms)	10-500	60
c. Total Flash Duration (ms)	30-1000	180
d. Total Charge Transfer (C)	350	15
e. Action Integral [$\int I^2 dt$] (A^2s)	$3x10^6$	$5x10^4$

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[1]The entire cloud-to-ground discharge may be comprised of multiple individual major current pulses. These are known as return strokes or, simply strokes.

[2]Continuing currents can occur between individual strokes, following the final stroke in a flash, or both.

Table 2
Direct-Strike Lightning Environment Recommended by the Present Study. Note That the 50% and 1% Columns are Reversed in Order from Table 1.

	50%	1%
RETURN STROKE PARAMETERS		
NEGATIVE FIRST STROKES		
(a) Peak Current (kA)	30	150
(b) Time to Current Peak (μs)	5	30
(c) Maximum Rate of Current Rise (kA/μs)	100	400
(d) Time to Decay to Half-Peak Value (μs)	70-80	300
(e) Charge Transfer (C)	5	40
POSITIVE FIRST STROKES		
(a) Peak Current (kA)	35	500
(b) Time to Current Peak (μs)	10-20	150
(c) Maximum Rate of Current Rise (kA/μs)	100	400
(d) Time to Decay to Half-Peak Value (μs)	†	†
NEGATIVE SUBSEQUENT STROKES		
(a) Peak Current (kA)	10-15	50
(b) Time to Current Peak (10-90 Percent) (μs)	0.3-0.6	9
(c) Maximum Rate of Current Rise (kA/μs)	100	400
(d) 10 to 90 Percent Rate of Current Rise (kA/μs)	30-50	150
(e) Time to Decay to Half-Peak Value (μs)	30-40	250
NEGATIVE CONTINUING CURRENT LONGER THAN 40 ms		
(a) Amplitude (A)	100-200	1000
(b) Duration (ms)	100	600
(c) Charge Transfer (C)	10-20	200
POSITIVE CONTINUING CURRENT		
(a) Amplitude (kA)	1	10
(b) Duration (ms)	85	1000
(c) Charge Transfer (C)	80	700
NEGATIVE FLASH PARAMETERS		
(a) Number of Strokes	3-5	25
(b) Interstroke Interval (ms)	60	600
(c) Duration (ms)	200	1000
(d) Charge Transfer (C)	20	200
(e) Action Integral (A^2s)	$8x10^4$	$3x10^6$
POSITIVE FLASH PARAMETERS		
(a) Number of Strokes	1	3
(b) Duration (ms)	85	1000
(c) Charge Transfer (C)	80	700
(d) Action Integral (A^2s)	$7x10^5$	$6x10^7$

† See discussion under Section II (e)

All parameters listed are for lightning between the cloud and ground. The characteristics of intracloud or intercloud lightning are much less well studied but thought to be generally less severe. Comparison of Table 1 and Table 2 shows that we have presented more lightning parameters than did Fisher and Uman (1989) and that some of the common parameters differ significantly. We comment below on the choice of the parameters listed in Table 2.

a. "Decay to 1000 A": As Fisher and Uman (1989) recommend, this parameter of Table 1 has been eliminated from Table 2.

b. Return stroke peak current: The peak current data in Table 2 for positive first strokes (rarely are there positive subsequent strokes – see Positive Flash Parameters in Table 2) and for first and subsequent negative strokes are taken from Berger et al. (1975) and their referenced previous work. The median (50%) values are relatively well established, and the 1% values are chosen from fitting log-normal distributions to the measured data, although some experimental data were measured near the 1% values of the data-fitting curve.

c. Maximum rate of return stroke current rise and other rise-time characteristics: In tower measurements such as made by Berger et al. (1975) this parameter is underestimated because of measurement system limitations and the potential influence of the strike object. Schoene et al. (2008) have shown that the strike object can affect rise-time parameters and that the highest rate of rise is for a well grounded object. The value of 100 kA/μs adapted as the 50% maximum rate-of-rise both for positive strokes and for negative first and subsequent strokes has been measured on well-grounded strike objects for negative strokes in triggered lightning, those strokes being similar, if not identical, to subsequent strokes in natural lightning (Schoene et al. 2008; Depasse 1994; Fisher et al.

1993). The inference that the same 50% maximum rate of rise of current characterizes negative and positive first strokes as is measured for negative subsequent strokes follows from the observation that the maximum rate of change of the remote electric field for the three types of strokes striking well-conducting salt water is essentially the same (e.g., Krider et al. 1996; Cooray et al. 1998). The 1% maximum rate-of-rise-time of 400 kA/µsec listed in Table 2 is near the largest value measured for a triggered-lightning return stroke, 411 kA/µs (Letienturier et al. 1991), and the largest value measured for lightning interaction with an aircraft in flight, 380 kA/µs (Pitts et al. 1987). Return stroke rise-time characteristics such as time to peak and 10 to 90% rise-time are determined from measured triggered-lightning current waveforms and tower current waveforms (primarily Berger et al. (1975) and the references therein) with comparison of the measured current characteristics to electric field and electric field derivative measurements for lightning over salt water being used to infer current characteristics not adequately measured directly.

d. Flash charge transfer: The charge transfer values in Table 2 are taken primarily from the experimental data of Berger et al. (1975) and a log-normal distribution fit to those measured data. For a positive flash, 700 C is inferred from the log-normal distribution fit as the 1% value, whereas the largest measured value from Berger et al. (1975) was 400 C at the 4% level. There have been a number of measurements of both positive and negative charge transfer between 300 and 1000 C for lightning in Japanese winter storms, with one positive charge transfer reported to exceed 3000 C (Miyake et al. 1992, Goto and Narita 1995). The International Standard IEC 62305-1,3 (2006) lists 300 C as a "severe" charge transfer for all flashes. Damage to metal surfaces by charge transfer is considered in Section IV.

e. Flash action integral: The values for action integral in Table 2 are taken from the data of Berger et al. (1975), references to their previous work given in that paper, and log-normal distribution extrapolations of those measurements. It is sometimes difficult to decide when a return stroke current ends and a continuing current begins, particularly for positive flashes which almost always exhibit large, long-duration variable currents following an initial current peak. If such long-duration currents are attributed to continuing current, then it is continuing current that makes the major contribution to the flash action integral value (and to the charge transferred). It follows that the "time to decay to half-peak value" is not well defined for positive first strokes. The International Standard IEC 62305-1,3 (2006) gives 10^7 A^2s for a "severe" first-stroke action integral, whereas we give 6 x 10^7 A^2s in Table 2 for the 1% value for a positive flash, consistent with the data of Berger et al. (1975).

f. Continuing current, negative and positive: Duration data for negative continuing current longer than 4 ms taken from the high-speed video measurements of Campos et al. (2007) indicate that 15 ms is at the 50% level and 550 ms is at the 1% level. Kitagawa et al. (1962) report, from electric field measurements, that half of all negative ground flashes exhibit continuing current intervals exceeding 40 ms. Kitagawa et al. (1962) term continuing currents exceeding 40 ms "long continuing current". In Table 2, we present data only for long continuing currents.

g. Other parameters: The best overall discussion of the parameters not discussed in (a) – (e) above, for which there would not be much argument and which are not particularly critical to induced or direct lightning effects, is found in Rakov and Uman (2003), which is also a source for further information on the parameters discussed above in (b) – (f).

III. Time-Domain Waveforms for First Strokes, Subsequent Strokes, and Continuing Current.

We present functional expressions for current vs. time, current derivative vs. time, second current derivative vs. time, charge transfer vs. time, and action integral (specific energy) vs. time for first strokes, subsequent strokes, and continuing current using the approach suggested by DeConti and Visacro (2007), following Heidler et al. (1999). Constants are chosen for these current-related expressions so that the waveforms approximate the various 50% parameters for negative lightning listed in Table 2. The resultant waveforms can be considered typical. The current-related waveforms can be altered by changing the constants found in the functional expressions. At the end of this section we will suggest constants to produce "severe" waveforms.

General: General functional expressions for the return stroke and continuing current waveforms are given below. There are four constants ($I0_k, n_k, \tau 1_k, \tau 2_k$) for each term in the summations. The constant $I0_k$ controls the amplitude, n_k controls the initial waveform steepness, $\tau 1_k$ is the front-time constant, $\tau 2_k$ is the decay-time constant, and η_k is termed the amplitude correction factor.

Current: $$i(t) = \sum_{k=1}^{m} \frac{I0_k}{\eta_k} e^{-\frac{t}{\tau 2_k}} \frac{\left(\frac{t}{\tau 1_k}\right)^{n_k}}{\left(1+\frac{t}{\tau 1_k}\right)^{n_k}} \qquad (1)$$

with $\eta_k = e^{\frac{\tau 1_k}{\tau 2_k}\left(n_k \frac{\tau 1_k}{\tau 2_k}\right)^{\frac{1}{n_k}}}$

Current derivative: $$i'(t) = \sum_{k=1}^{m} \frac{e^{-\frac{t}{\tau 2_k}} \left(\frac{t}{\tau 1_k}\right)^{n_k} \left[t - n_k \tau 2_k + t\left(\frac{t}{\tau 1_k}\right)^{n_k}\right] I0_k}{t\left[\left(\frac{t}{\tau 1_k}\right)^{n_k} + 1\right]^2 \eta_k \tau 2_k} \qquad (2)$$

Current second derivative:

$$i''(t) = \sum \frac{e^{-\frac{t}{\tau 2_k}} \left(\frac{t}{\tau 1_k}\right)^{n_k} I0_k \left[n_k (\tau 2_k)^2 - 2t^2 \left(\frac{t}{\tau 1_k}\right)^{k} - t^2 - n_k{}^2 (\tau 2)^2 - t^2 \left(\frac{t}{\tau 1_k}\right)^{2n_k} + 2tn_k \tau 2_k\right]}{t^2\left[\left(\frac{t}{\tau 1_k}\right)^{n_k} + 1\right]^3 \eta_k (\tau 2_k)^2} +$$

$$\frac{I0_k\left[\left(\frac{t}{\tau 1_k}\right)^{n_k} n_k (\tau 2_k)^2 + \left(\frac{t}{\tau 1_k}\right)^{n_k} n_k{}^2 (\tau 2)^2 + 2t\left(\frac{t}{\tau 1_k}\right)^{n_k} n_k \tau 2_k\right]}{t^2\left[\left(\frac{t}{\tau 1_k}\right)^{n_k} + 1\right]^3 \eta_k (\tau 2_k)^2} \qquad (3)$$

Charge transferred: $$\int i(t)dt = \int \sum_{k=1}^{m} \frac{I0_k}{\eta_k} e^{-\frac{t}{\tau 2_k}} \frac{\left(\frac{t}{\tau 1_k}\right)^{n_k}}{\left(1 + \frac{t}{\tau 1_k}\right)^{n_k}} dt \qquad (4)$$

Action integral: $$\int i^2(t)dt = \int \left[\sum_{k=1}^{m} \frac{I0_k}{\eta_k} e^{-\frac{t}{\tau 2_k}} \frac{\left(\frac{t}{\tau 1_k}\right)^{n_k}}{\left(1 + \frac{t}{\tau 1_k}\right)^{n_k}}\right]^2 dt \qquad (5)$$

Subsequent Stroke: To synthesize a typical subsequent stroke waveform, one Heidler function is used, i.e., m = 1 only in the expressions above. The values for the parameters are given in Table 3. The plots for the current, the first derivative of the current and the second derivative are shown in Fig.1, Fig.2, and Fig.3, respectively. The parameters obtained from the plotted waveforms are given in Table 4.

Table 3. Calculated Values of Heidler Function Parameters for a Subsequent Stroke Current

$I0(kA)$	n	$\tau 1(\mu s)$	$\tau 2(\mu s)$
15	5	0.2	50

Table 4. Measured Parameters of Waveform Synthesized Using Parameters From Table 3.

$I_{peak}(kA)$	$\left(\frac{di}{dt}\right)_{max}(kA/\mu s)$	$\tau_{10to90risetime}(\mu s)$	$\tau_{Peakto50decaytime}(\mu s)$
15	98	0.18	31

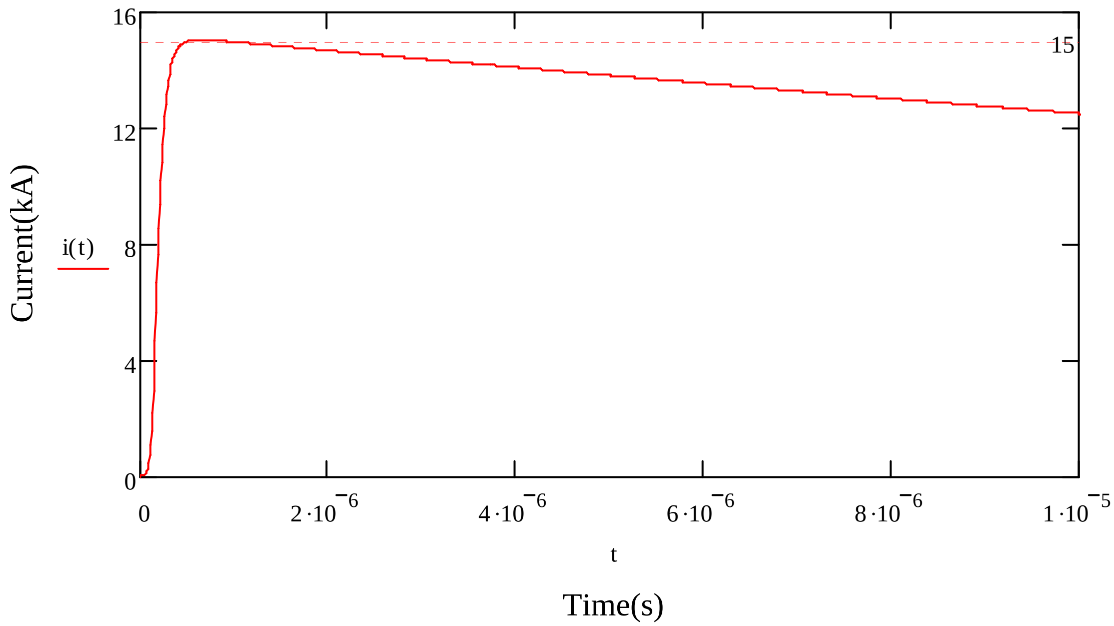

Fig 1. Subsequent Stroke Current Waveform. The Peak Current is Shown.

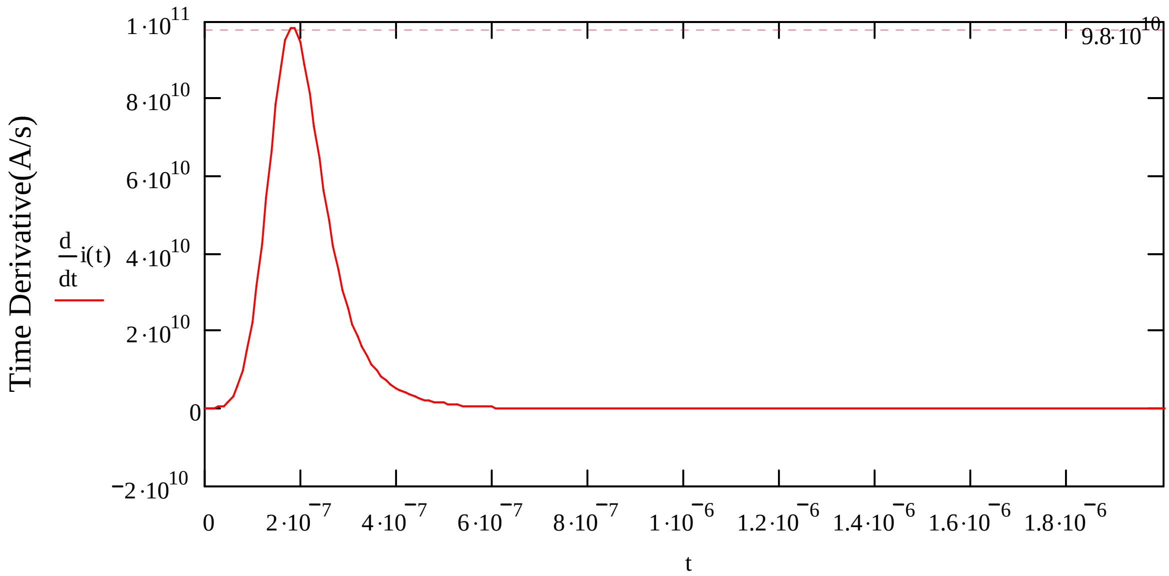

Fig 2. First Time Derivative of Subsequent Stroke Current. The Maximum Derivative is Shown.

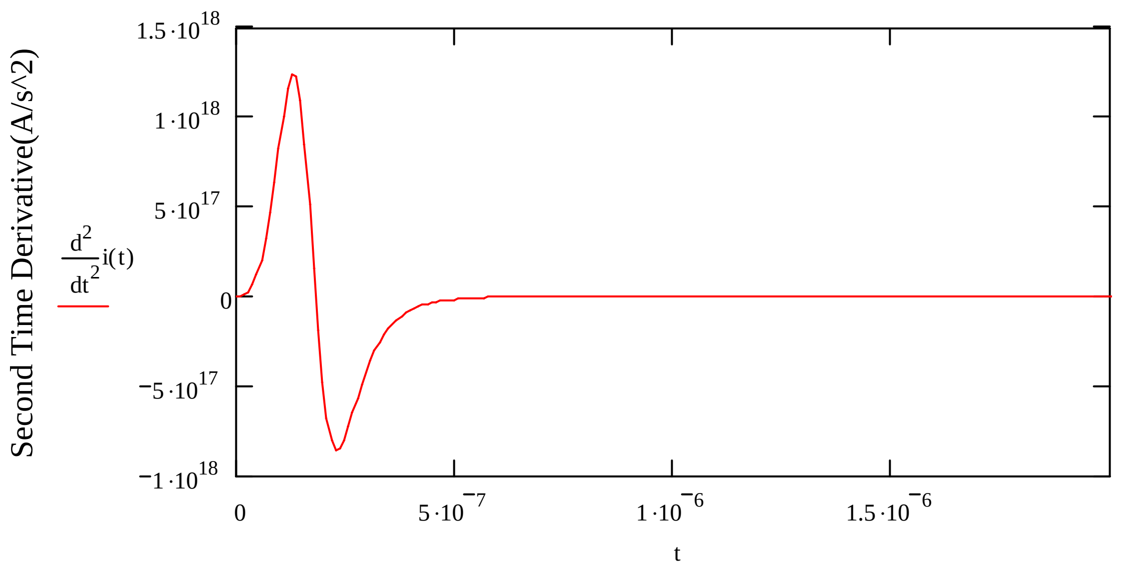

Fig 3. Second Time Derivative of Subsequent Stroke Current.

First Stroke: For a first stroke waveform, 6 Heidler functions (m = 1 - 6) are summed. The parameters used for each Heidler function are shown in Table 5. Fig. 4 shows the current. Fig. 5 shows the first derivative of the current, and Fig. 6 shows the second derivative. The parameters measured from the plotted waveforms are shown in Table 6.

Table 5. Calculated Values of Heidler Function Parameters for a First Stroke Current

K	$I0_k\,(kA)$	n_k	$\tau 1_k\,(\mu s)$	$\tau 2_k\,(\mu s)$
1	3	2	15	30
2	3	3	15	30
3	3	9	20	30
4	3	11	20	30
5	25	150	10	23
6	15	2	30	250

Table 6. Measured Parameters of First Stroke Waveform Synthesized Using Parameters From Table 5.

$I_{peak}\,(kA)$	$\left(\frac{di}{dt}\right)_{max}\,(kA/\mu s)$	$\tau_{10to90risetime}\,(\mu s)$	$\tau_{Peakto50decaytime}\,(\mu s)$
34	97	3.1	77

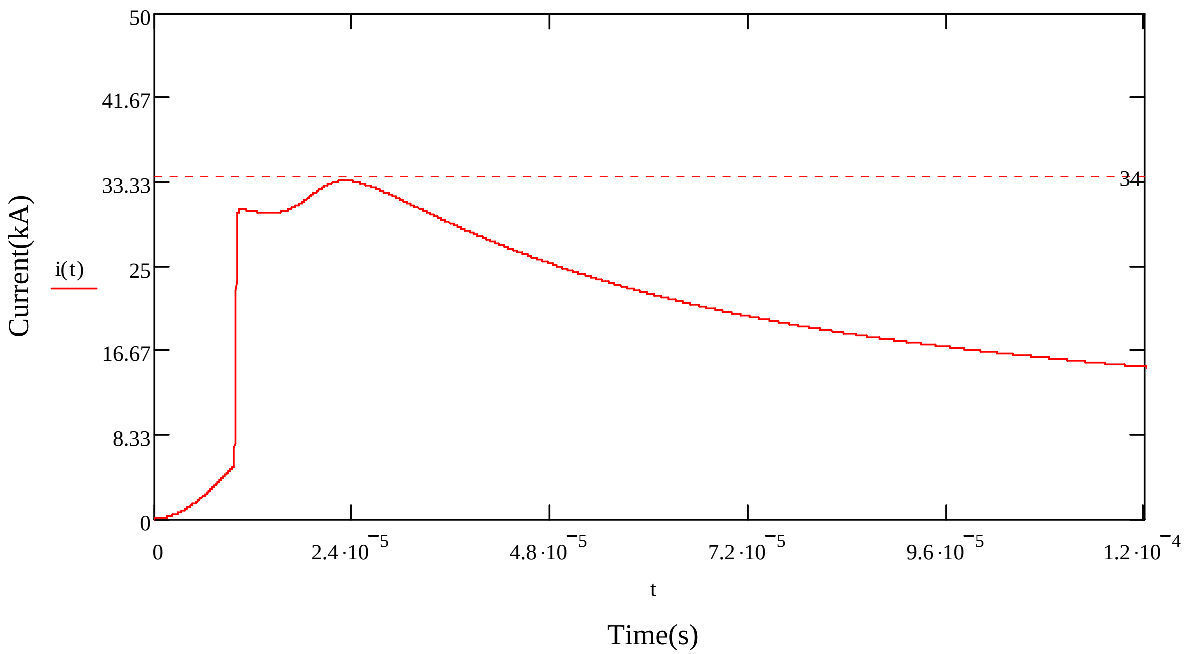

Fig 4. First Stroke Current Waveform. Peak Current is Shown.

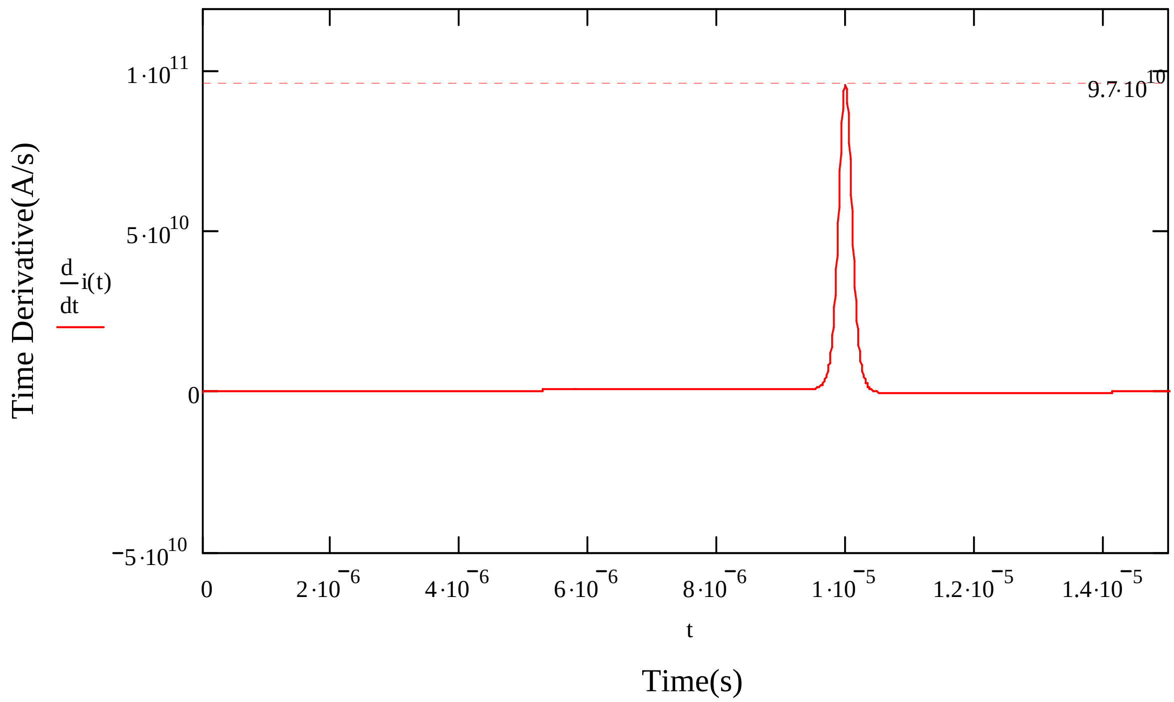

Fig 5. First Time Derivative of First Stroke Current Waveform. Maximum Derivative is Shown.

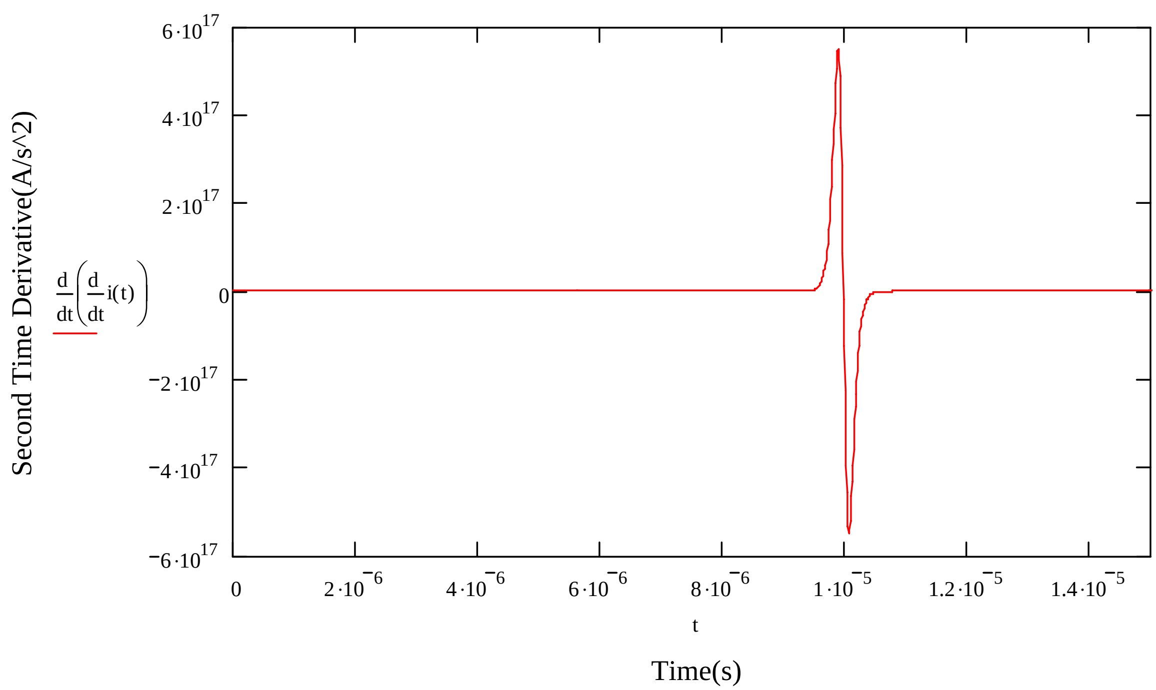

Fig 6. Second Time Derivative of First Stroke Current Waveform.

The first stroke current rise to peak value consists of a "slow front" of some microseconds followed by a "fast transition" of tenths of a microsecond to the peak value during which time the maximum current derivative occurs, as observed on towers in Switzerland (Berger et al. 1975), Brasil (DeConti and Visacro 2007), and as inferred from electric field measurements (e.g., Jerauld et al. 2007). For the first-stroke constants given, the first-stroke charge transfer is 4 C, and the action integral is 10^5 A^2s.

Continuing current: One Heidler function is used to produce the waveform (Figure 7) for the negative continuing current. The values for the parameters are summarized in Table 7. Quantities measured from the analytical waveform are found in Table 8. Figure 8 and 9 show the first and the second time derivative of the current waveform, respectively. The action integral is $1.08*10^5$ A^2s

Table 7. Calculated Values of Heidler Function Parameters for Continuing Current

$I0(A)$	n	$\tau 1(\mu s)$	$\tau 2(ms)$
200	2	25	100

Table 8. Measured Parameters of Waveform Synthesized Using Parameters From Table 7.

$I_{peak}(A)$	$\left(\frac{di}{dt}\right)_{\max}(A/\mu s)$	Total Charge(C)	$\tau_{Peakto50decaytime}(ms)$
205	5.35	12.92	70

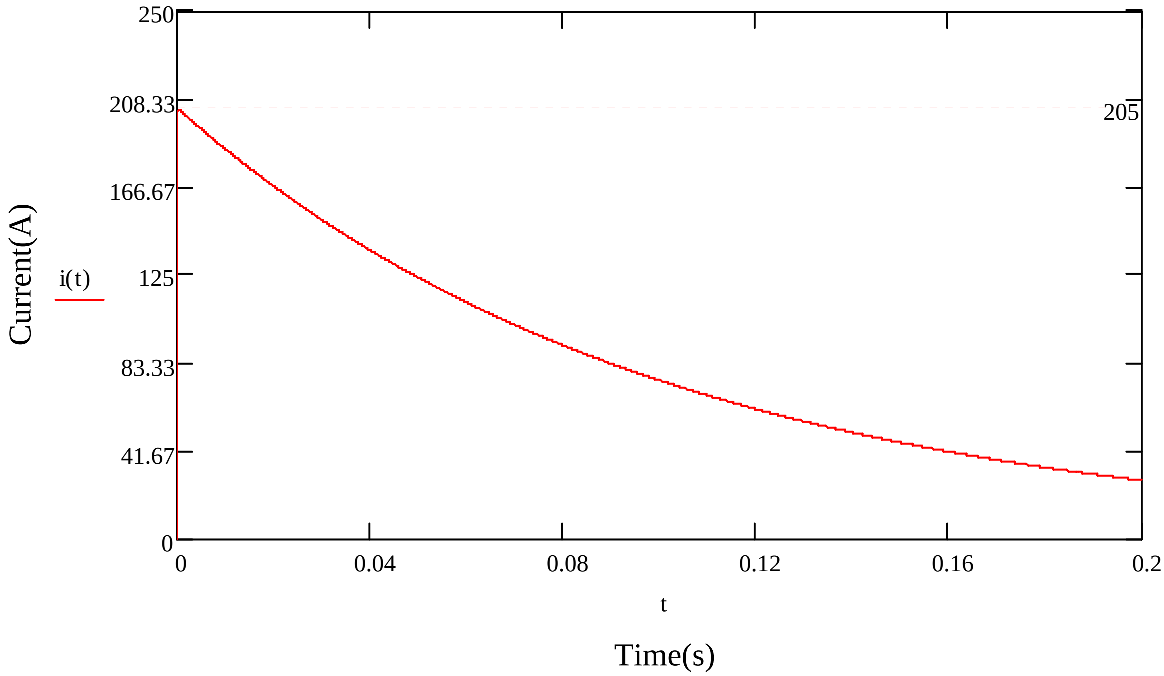

Fig 7. Negative Continuing Current Waveform. Peak Current is Shown.

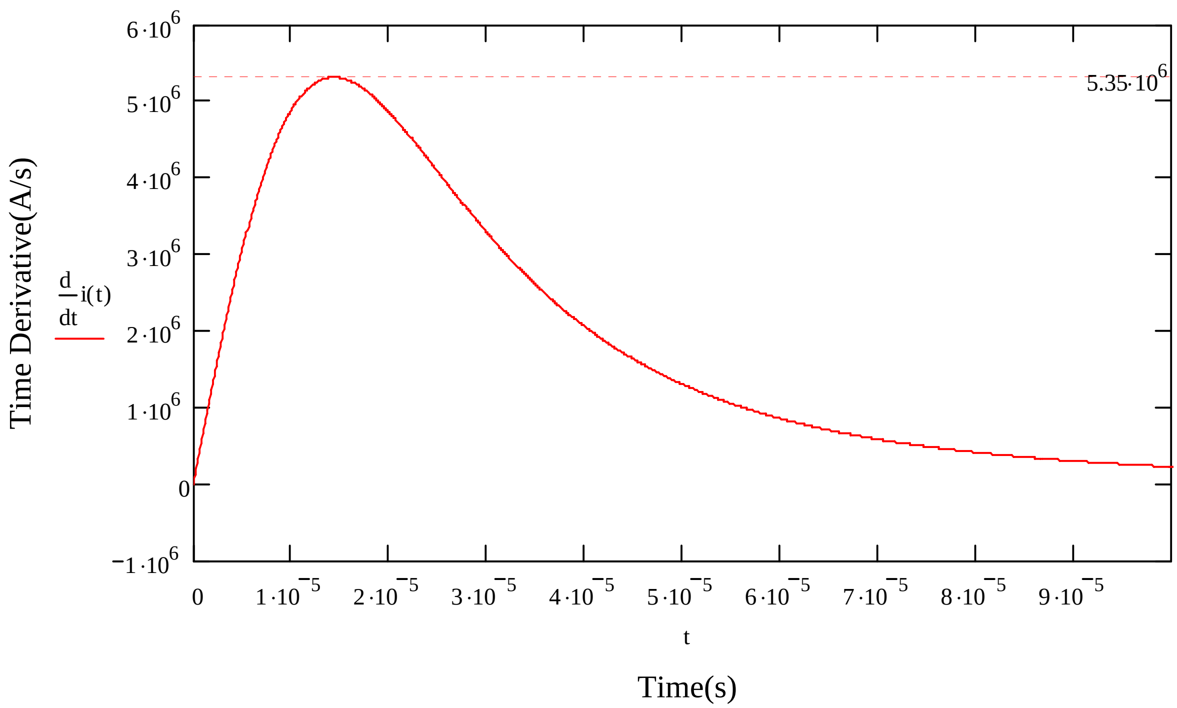

Fig 8. First Time Derivative of Continuing Current Waveform. Maximum Derivative is Shown.

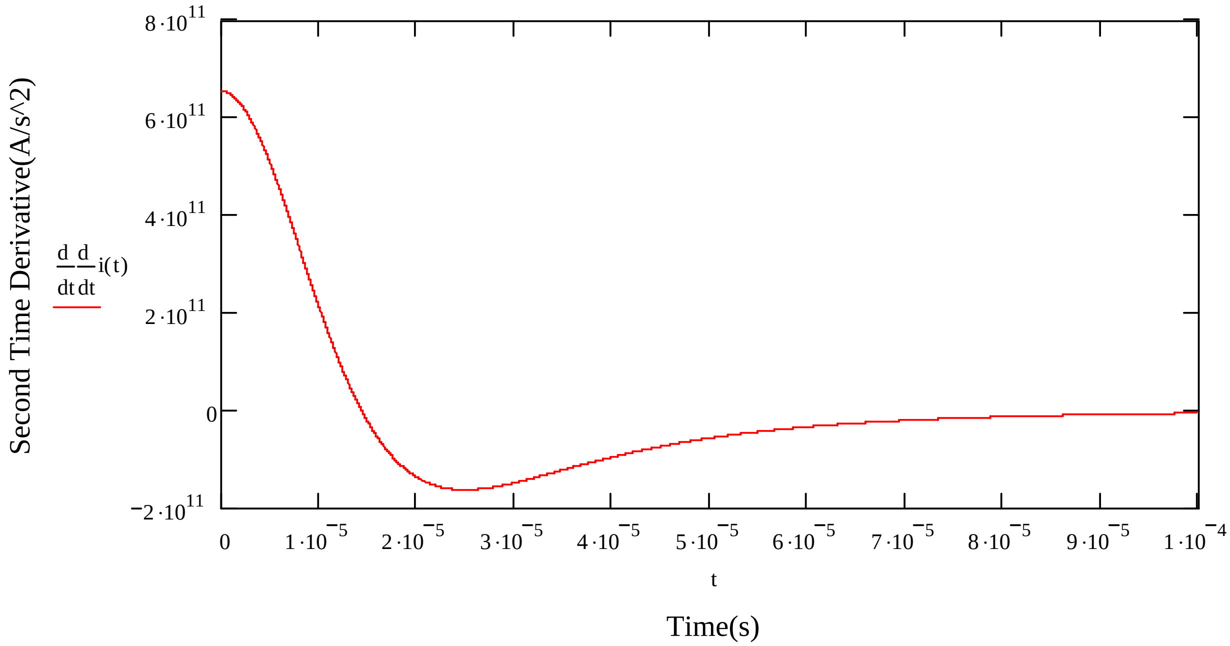

Fig 9. Second Time Derivative of First Stroke Current Waveform.

<u>Severe (1%) Parameters</u>: Functional expressions are given above for negative first and subsequent strokes and for continuing current. Constants are given to produce the median parameters found in Table 2. To simulate a reasonable approximation to a negative flash having all 1% parameters, multiply the first and subsequent stroke current amplitudes for the median case by a factor of 5 and the continuing current amplitude for the median case by a factor of 10.

IV. Damage to Metal Surfaces by Lightning Currents

Nuclear waste materials are to be stored and transported in various containers (casks) that are, in part, composed of multiple, concentric, closed-metal shells. For example, the nuclear waste cask type TEV (Transportation and Emplacement Vehicle) has a 1/2"-thick outer stainless steel shell separated from an inner 1 ½ "-thick stainless steel shell by 6" of polymer material. Within the inner shell is 1 ½ " of depleted uranium and within that another ½"-thick stainless steel container. The nuclear waste is contained inside the latter ½"-thick stainless steel container. Other casks have equivalent or greater shielding than type TEV. For example, the NUHOMS

MP197 Package has a 2 ½"-thick outer layer of stainless steel with 3 ¼" of lead and 1 ¼" of stainless steel inside of the outer layer.

The critical question is whether an extreme direct lightning strike could penetrate nuclear waste containers such as those described above. To answer this question we have surveyed the pertinent literature on lightning damage to metal surfaces, the few significant papers being listed in Appendix 4, and we have performed tests on ¾"-thick and ½"-thick stainless steel plates using triggered-lightning currents.

The physical mechanisms by which lightning or laboratory arcs deliver energy to metal surfaces and the resultant damage of those surfaces is reviewed by Testé et al. (2000). The power density Q delivered to a metal surface is

$$Q = J_e \, F_N \ \text{Watts/m}^2 \qquad (6)$$

where J_e is the electron current density to the surface in Amps/m^2 and F_N is called the Nottingham potential, the potential drop in Volts at the surface due to the work function of the metal and other parameters contributing to the voltage drop between the tip of the arc and the metal. The Nottingham potential is generally in the range 5 to 10 Volts and the range of the electron current density has extremes of 10^8 and 10^{12} Amps/m^2, but generally is 10^9 to 10^{10} Amps/m^2 for a reasonable range of metals and currents. If, for example, $J_e = 10^9$ A/m^2 and a lightning continuing current of 10^3 Amps flows, the surface area over which the current supplies input power is 1 mm. The total power, P, delivered to a small spot on a metal surface is

$$P = I_e \, F_N \ \text{Watts} \qquad (7)$$

and the total energy, W, delivered to the surface is the integral over time of P which, if F_N is roughly constant with changing current, as appears to be the case, is

$$W = Q_e \, F_N \ \text{Joules} \qquad (8)$$

where Q_e is the total charge delivered to the surface. Testé et al. (2000) give references to various published papers describing in more detail the experiments and theory leading to the formulation given above. Of most significance is the fact that from Eq.(8) the input energy is, to first approximation, linearly proportional to the charge delivered to the metal surface.

The energy input to the metal surface produces a temperature rise and melting, and further heating of the melted metal. The greatest amount of penetration perpendicular to the metal surface occurs when the arc does not wander on the metal surface. Short arcs tend not to wander and long arcs which penetrate a thin insulating surface material covering the metal such as metal oxide or paint can be held in place by that surface material. In general, magnetic forces will cause the arc root of a long arc to wander (see next paragraph). Bellaschi (1941), McEachron and Hagenguth (1942), and McEachron (1949) describe damage to metal surfaces from natural lightning and from laboratory arcs. They all show experimentally that there is a linear relationship between (1) both the amount of metal melted and the area of the holes melted in thin metal sheets and (2) the total charge delivered to the metal by the current, consistent with Eq. (8). McEachron and Hagenguth (1942) illustrate that it is the charge transfer that is important to the degree of damage and not the action integral, as would be the case if I^2R heating of the metal were important, by applying different arc currents for different lengths of time to metal surfaces. Bellashci (1941) showed experimentally that, for copper, there was an average of about 1 cubic mm of metal fused for each 2 Coulombs of charge transferred to the copper surface, independent of electrode polarity, and stated that the same result was expected for iron, considering its physical properties. He also showed experimentally, that the Nottingham potential F_N in Eq. (6) for copper was about 6 Volts and that a charge of 1790 Coulombs (above the 1% value for both negative and positive lightning – see Table 2) fused about 1 cm^3 of copper.

McEachron and Hagenguth (1942) applied 430 Coulombs (above the 1% level for negative lightning but below that level for positive lightning – see Table 2) to a 3/8" thick sheet steel plate and formed a crater of 3/16" depth and 180 mm^2 area. They stated that several thousand Coulombs (above the 1% level for either negative or positive lightning) would be required to puncture the 3/8" thick steel plate.

Triggered-lightning experiments have been used to measure the damage to metal surfaces from lightning charge transfer. Schnetzer and Fisher (1992) show that about 40 C of lightning charge, delivered in a 4-stroke flash, to a 0.05-inch thick stainless steel sample does not burn through the sample but rather make a number of separate damage spots on it, each spot being about 0.1 inch in diameter, because the location of the arc root moves during the flash. Similar damage structure is seen for a lightning charge of about 90 C, of which 78 C is in continuing current, to a 0.08-inch thick copper sample. In mid-summer 2008 we set up our own triggered-lightning experiments at the UF-FIT International Center for Lightning Research and Testing (ICLRT) in which triggered-lightning current is intended to impact ½-inch thick and ¾-inch thick stainless steel plates simulating cask material. These experiments remain active, but we have only been able to trigger lightning to the plates once, primarily because tropical storms have suppressed the more usual Florida summer convective thunderstorm activity. That one event occurred on September 17, 2008, to late to be included in this report.

It follows from the above (experiment and theory) that it is extremely unlikely that any known lightning charge transfer could penetrate a ½" thick outer layer of stainless steel that comprised the outer wall of a nuclear storage cask, and, for existing and planned casks, there are multiple layers of such steel and other materials surrounding the nuclear waste, providing additional safety.

V. Measurement of the Characteristics of Positive Lightning

In May of 2008, an experiment was begun to measure the electric and magnetic fields produced by cloud to ground lightning of positive polarity occurring within about 10 km of the International Center for Lightning Research and Testing (ICLRT). Prior to this experiment, the electric and magnetic field sensors at the UF-FIT research site were configured to measure lightning occurring within 1 km. To measure a statistically significant number of the more distant positive lightning flashes (those being ten times less common than negative flashes and potentially have higher peak currents, higher charge transfers, and longer continuing currents), the number of electric field sensors in the network was increased from six to ten, their relaxation times were increased from 1 s to about 5 s, and their gains were increased. Three different sensitivities were necessary to measure the full range of signal amplitudes produced by the different physical processes occurring in positive lightning at different distances. A second cross-looped magnetic field sensor with a higher sensitivity and longer relaxation time has been added to augment the original magnetic field sensor and the electric field measurements. In addition to these RF measurements, ten NaI-PMT, high-energy detectors have been added to the experiment to detect any x-rays produced by positive polarity discharges.

To date, data have been recorded for about 75 cloud to ground, positive lightning flashes, at distances of several kilometers to fifty kilometers. Data recorded after June 10, 2008, were synchronized to GPS time, and most of the data recorded after this date has been correlated to NLDN reports of positive lightning. Two examples of our data are given in Figures 10 and 11. Figure 10 shows data from the closest recorded positive cloud to ground lightning, occurring at a distance of about 2 km north-east of the ICLRT (no NLDN location - flash seen in that direction at time of data record, thunder heard within seconds). Figure 10a shows the data on a time scale of 700 ms, and Figure 10b shows the data on a time scale of 3 ms. Figure 11 shows data recorded for an event that was reported by the NLDN as being a 190 kA, single-stroke, positive cloud to ground lightning, 25 km south of the ICLRT. Figure 11a shows the data on a time scale of 600 ms, and Figure 11b shows the data on a time scale of 500µs. From data such as is shown in Fig. 10 and Fig. 11, we hope to extract statistics on the continuing currents and charge transfer in Florida positive lightning. For example, the charge transferred by a positive return stroke can be calculated using the magnitude of the electrostatic field change in the following equation

$$\Delta Q = \frac{2\varepsilon_0 (H^2 + R^2)^{3/2}}{H} \Delta E \qquad (6)$$

where *H* is the altitude of the source charge, and *R* is the distance to the return stroke from the sensor. Figure 12 shows the full-length electric field waveform of the event shown in Figure 11, with an electrostatic field change of about 700 V/m marked. That electrostatic field change is also evident in Fig. 11a, antenna E-5. Assuming this flash was 25 km away and that the charge source was at an altitude of 8 km, the total charge transferred was about 88 C, near the median value of 80 C listed in Table 2.

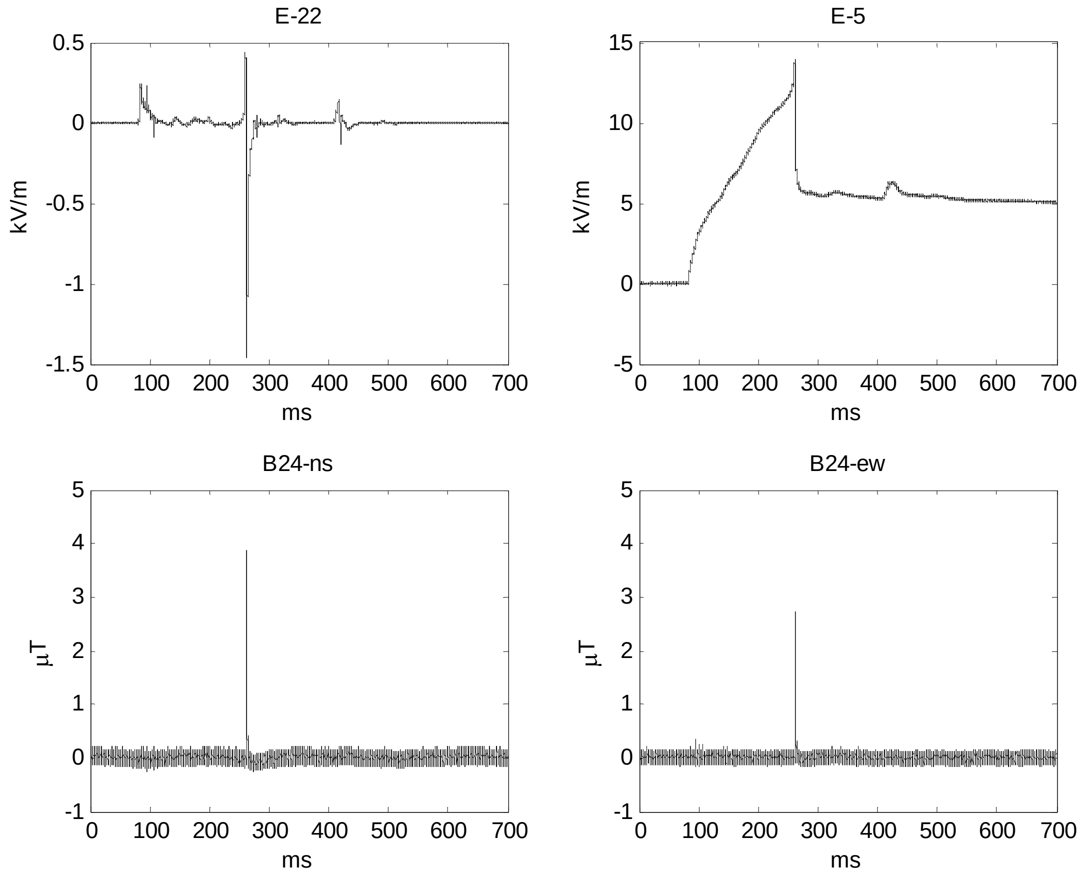

Figure 10a. The electric (E) and magnetic (B) fields of a positive, cloud to ground lightning that occurred about 2 km north-east of the ICLRT. Note that E-22 has a fast relaxation time, about 5 ms, and E-5 has a longer relaxation time of about 5 s.

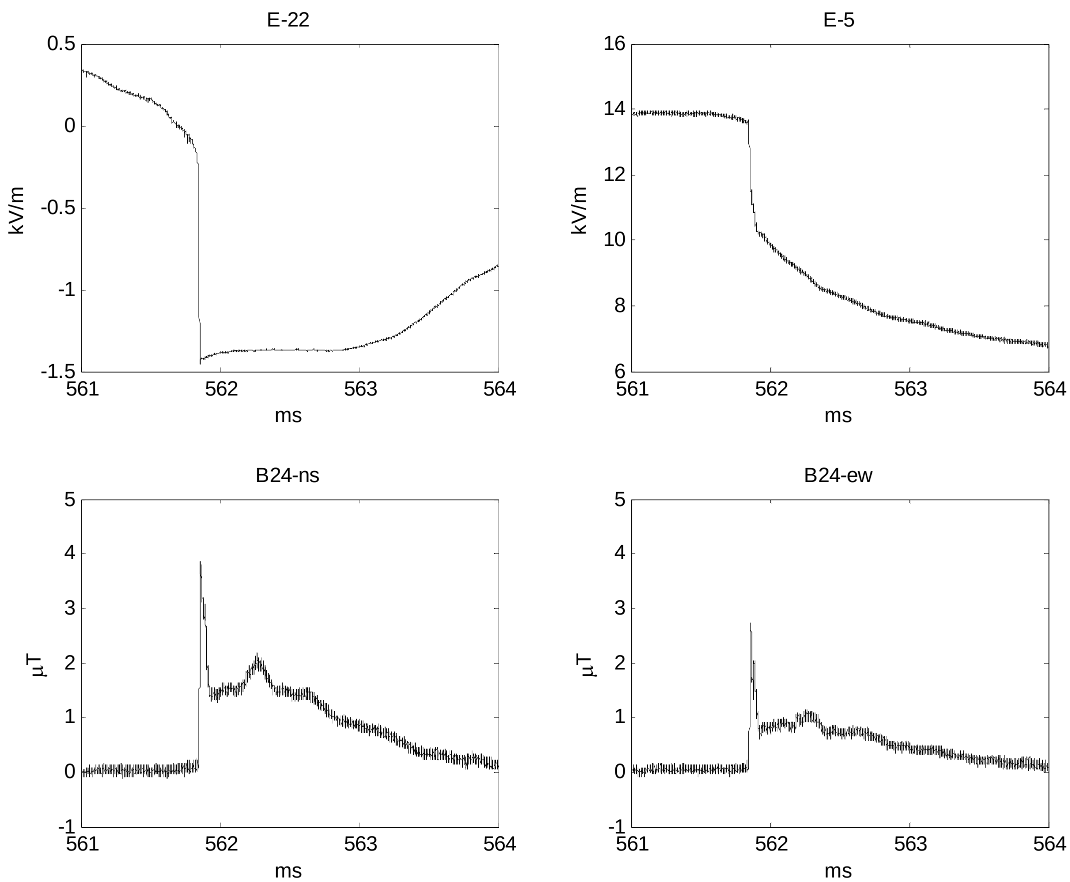

Figure 10b. A zoomed-in view of the data presented in Figure 10a. E-22 saturates at about 561.8 ms, and stays saturated until after 563 ms. Note that the magnetic field measurements are the old sensors, which are configured to measure on-site lightning, and have a relaxation time of about 15 ms.

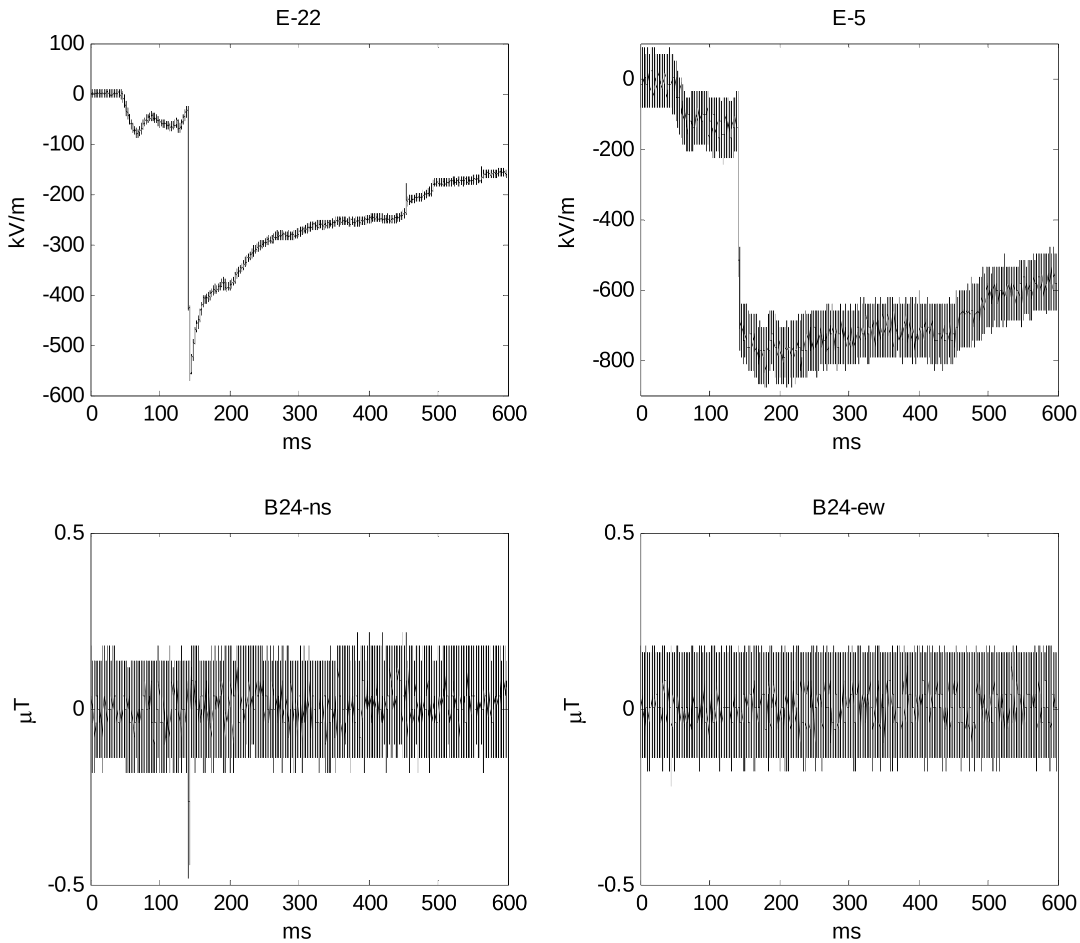

Figure 11a. The electric (E) and magnetic (B) fields of a positive, cloud to ground lightning that was reported by the NLDN as having a peak current of 190 kA, and occurring 25 km south of the ICLRT.

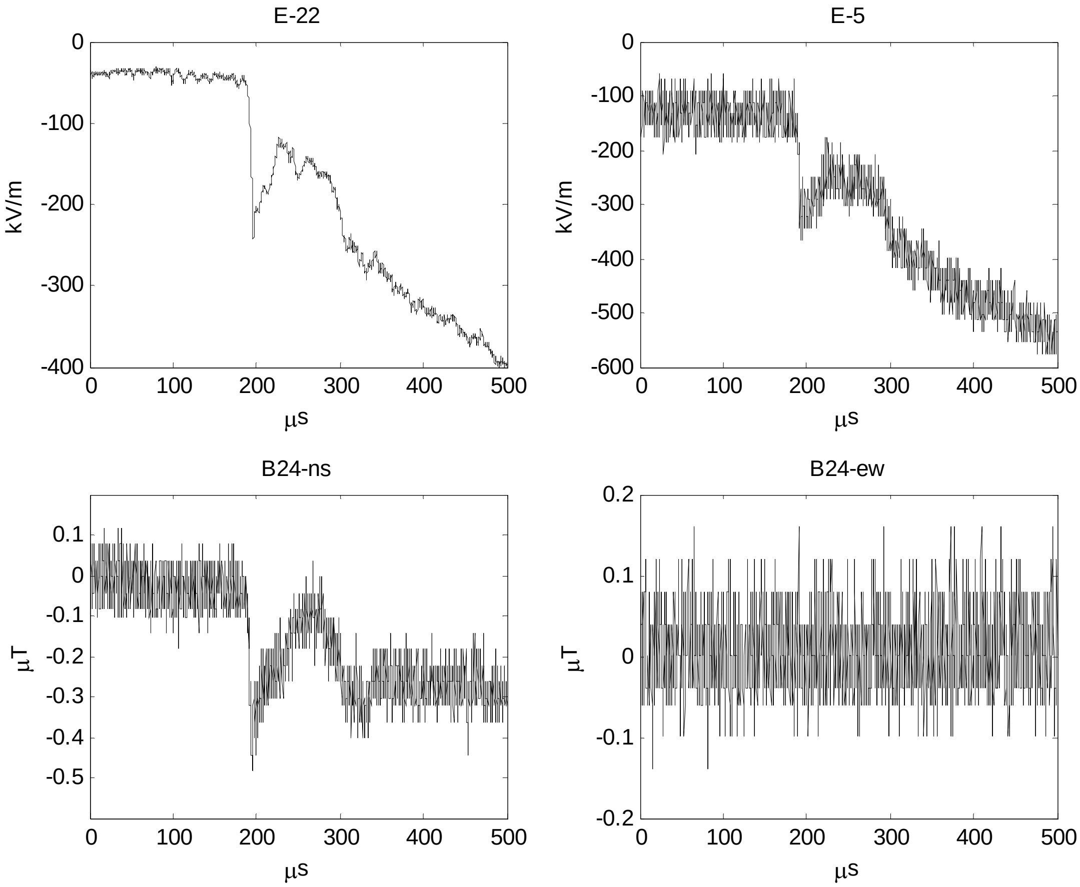

Figure 11b. A zoomed-in view of the data presented in Figure 11a. Note the visible leader steps in the E-22 record.

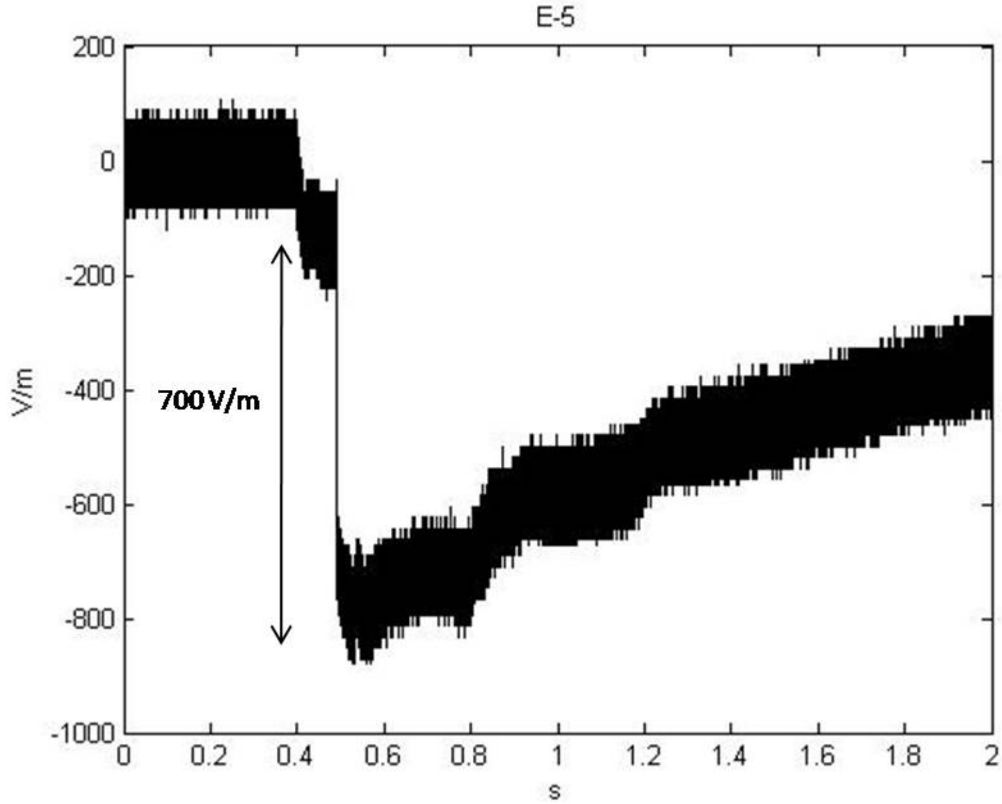

Figure 12. The full two-second electric field record for the flash shown in Figure 11. After the total electrostatic field change which occurs in tenths of a second, the electric field signal decays with the system's 5 second time constant. The overall electrostatic field change is about 700 V/m and the calculated charge transfer was about 88 C.

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Appendix 1: Return Stroke Current

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Appendix 2: Continuing Current

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Appendix 3: Positive Lightning

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Appendix 4: Lightning Damage to Metal Surfaces

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