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Update Direct-Strike Lightning Environment for Stockpile-to-Target Sequence Supplement LLNL Subcontract #B568261

Lightning Protection at the Yucca Mountain Waste Storage Facility

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Update Direct-Strike Lightning Environment for Stockpile-to-Target Sequence: Supplement LLNL Subcontract # B568621
Lightning Protection at the Yucca Mountain Waste Storage Facility

Final Report
to
Lawrence Livermore National Laboratory
from the
University of Florida
Department of Electrical and Computer Engineering
by
Martin A. Uman

Executive Summary

The University of Florida has surveyed all relevant publications reporting lightning damage to metals, metals which could be used as components of storage containers for nuclear waste materials. We show that even the most severe lightning could not penetrate the stainless steel thicknesses proposed for nuclear waste storage casks.

TABLE OF CONTENTS

I. Introduction

A lightning direct-strike environment specification for nuclear weapons protection was published in 1989 by R. J. Fisher of the Sandia Corporation and Martin A. Uman of the University of Florida (Fisher and Uman, 1989). As part of a 2008 Lawrence Livermore National Laboratory grant, to which "Lightning Protection at Yucca Mountain Waste Storage Facility" is a subcontract, the University of Florida has surveyed all relevant publications reporting lightning characteristics and has formulated an up-to-date version of the 1989 Fisher-Uman direct-strike specifications. That specification is given in Table 1, taken from the 2008 LLNL grant final report (Update Direct-Strike Lightning Environment for Stockpile-to-Target Sequences, LLNL-SR-407603, Sept. 30, 2008), so as to establish the lightning parameters that might be encountered by stored nuclear material. The values in Table 1 are taken from a variety of specific sources listed and discussed in the 2008 LLNL final report, a general reference being Rakov and Uman (2003). As we shall see in the next section, lightning damage to metal surfaces can be viewed as caused, to a good approximation, solely by the lightning charge transfer. The flash charge transfer values in Table 1 are taken primarily from the experimental data of Berger et al. (1975) and a log-normal distribution fit to those measured data. For positive flashes, a charge transfer of 700 C is inferred as the 1% value from the log-normal distribution fit whereas the largest value measured by Berger et al. (1975) was 400 C, at the 4% level of the log-normal curve. 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. In Section II we provide data on the effects of direct strikes to metal surfaces, those metals, particularly stainless steel, being potential components of the proposed casks inside of which nuclear materials would be stored.

II. 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.

A key concern 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 significant papers being listed in the bibliography to this report, and we have set up tests to be performed on ½"-thick and 1 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

$$Q = J_e \, F_N \ \text{Watts/m}^2 \qquad (1)$$

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 is generally 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

$$P = I_e F_N \quad \text{Watts} \qquad (2)$$

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

$$W = Q_e F_N \quad \text{Joules} \qquad (3)$$

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. (3) 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 Hagenguth (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. (3). 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. (1) 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 1) 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 1) 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 actual 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 the surface, 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"- thick and 1 ½"- 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. Figure 1 shows the lightning damage caused by about 7 C of lightning charge transfer on a 1 ½"- thick stainless steel plate. The charge transfer is below the median value of 20 C (see Table 1). The depth of the damage spot is less than 1 mm, the diameter near 1 cm. Arc wander is evident. Scorching of the plate is also evident, particularly to the right and above the damage mark.

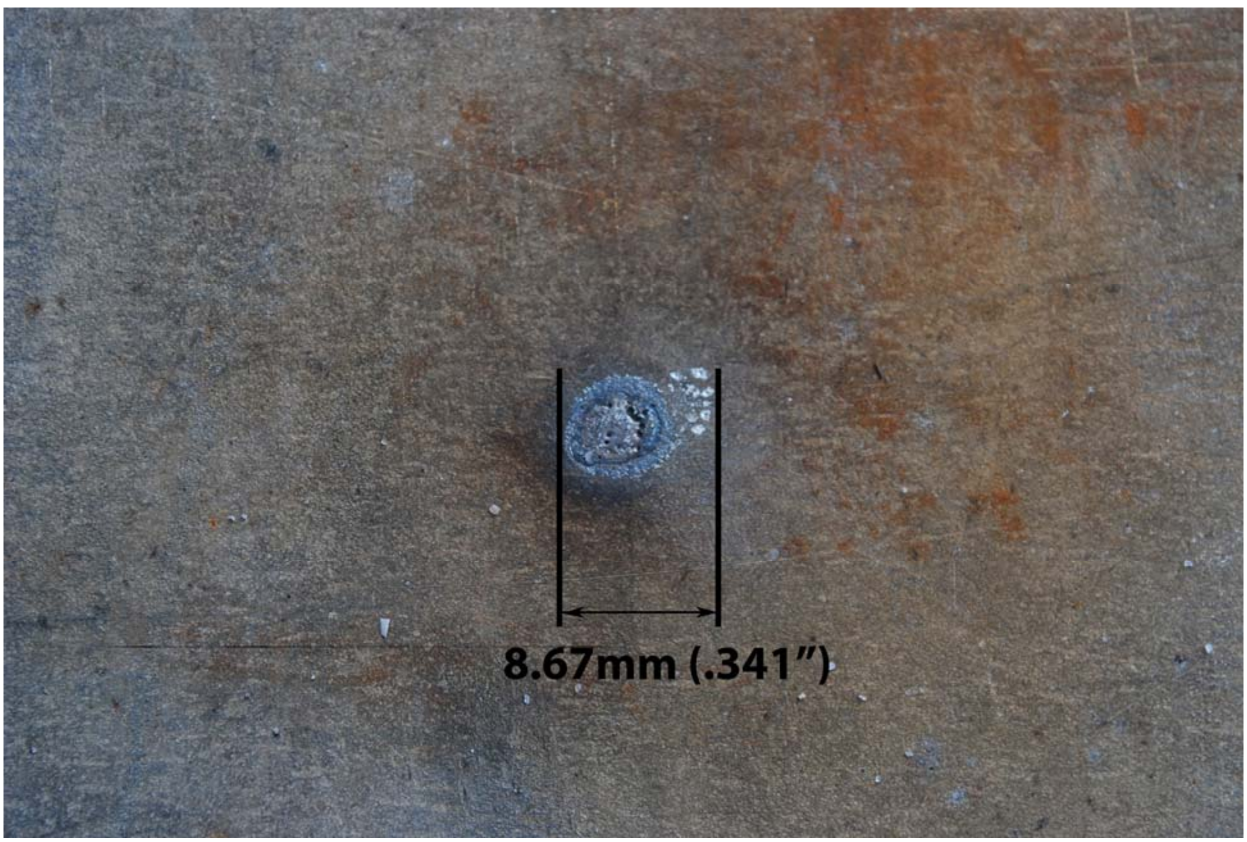

Fig. 1. Lightning damage to a stainless steel plate by about 7 C of lightning charge.

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.

Table 1

Direct-Strike Lightning Environment Recommended for the Present Study. Median parameters are labeled 50%. One percent of lightning events exceed the parameters labeled 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)

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