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Analysis and Development of a Personal Portable Lightning Protection System

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Escuela Doctoral

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2023

It is the glory of God to conceal a thing, but the glory of kings is to search out a thing. [Deut. 29:29; Rom. 11:33]

A prudent man perceives danger and seeks shelter, while the simple continue forward and pay for it.

Proverbs 22, 3

A mi esposa Margareth Andrea y a mis papás Bertha María y Luis Jorge (Q.E.P.D.)

In appreciation to the merciful God and his creation.

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Permissions and legal considerations

For this project does not apply. However, some ideas and concepts of the Colombian Patents 15131006, and 15131009 (2018) were used with the permission of the authors to the development of this thesis.

Análisis y desarrollo de un sistema de protección personal portátil contra rayos

Resumen

Colombia tiene una actividad de rayos muy alta como se muestra en diferentes mapas de rayos publicados. Cualquier actividad que se desarrolle a campo abierto durante una tormenta, más aún en lugares reconocidos como de alta actividad de rayos, en determinadas épocas y temporadas, aumenta aún más el riesgo de sufrir algún tipo de lesión para las personas expuestas. Los lugares remotos y de difícil acceso alejados de centros urbanos empeoran este escenario. Para el Ejército Nacional de Colombia se reporta en un promedio de quince años, hasta 48 soldados por año víctimas del impacto de rayos. Para reducir el riesgo del rayo a la salud en la población vulnerable que no puede evitar su exposición, se analizan los mecanismos más probables de lesión considerando algunos escenarios con modelos humanos existentes. Considerando que un refugio portátil para la protección contra rayos requiere materiales livianos, se investigaron en el laboratorio algunos tipos de tejidos electroconductores sometidos a corrientes impulsivas tipo rayo con forma de onda estándar. Algunas muestras de tejidos conductores se sometieron a varias corrientes de rayo subsecuentes y se analizaron, revelando algunos cambios notorios en su superficie. A pesar de los cambios morfológicos, entre los tejidos ensayados, un tejido conductor tipo *rip-stop* (anti-desgarro) mostró un gran potencial y resistió varias corrientes de impulso de rayo, sugiriendo su uso en refugios móviles para personas. Se propone un modelo de refugio portátil básico al cual se le realizan ensayos de laboratorio. Los resultados muestran que el modelo de refugio básico propuesto podría proteger a los seres humanos contra el aumento del potencial de tierra (EPR – *earth potential rise*) minimizando el riesgo causado por una descarga de rayo cercana.

Palabras clave: *Protección contra el rayo, sistemas portátiles de protección contra el rayo, tejidos conductores, ensayos de alta corriente, tiendas de campaña, refugios, tejidos electroconductores.*

Analysis and Development of a Personal Portable Lightning Protection System

Abstract

Colombia has a very high lightning activity as shown in different published lightning maps. Any activity that takes place outdoors in stormy weather, even more in places recognized as having high lightning activity, at certain times and seasons, increases even more the risk of suffering some type of injury for exposed people. Non-accessible places, such as remote and backcountry locations, worsen this scenario. It is reported for the Colombian National Army in fifteen-year averages, up to 48 soldiers per year victims of lightning strikes. To reduce the lightning risk to health in vulnerable population that cannot avoid their exposure, the most probable mechanisms of injury are analyzed considering some scenarios with existing human models. As a portable shelter requires lightweight lightning protection materials, some types of electroconductive fabrics against standard lightning impulse currents were investigated in the laboratory. Some samples of conductive fabrics were subject to several subsequent lightning-like currents and analyzed, revealing some patterns changes on its surface. Despite the morphological changes, among the tested fabrics, a ripstop conductive fabric showed great potential and proved capable of withstanding several lightning impulse currents, suggesting its suitability for use in personal mobile shelters. A model of a basic portable shelter is proposed and tested in the laboratory. The results show that the basic shelter model can protect human beings against the earth potential rise (EPR) minimizing the risk caused by a close lightning discharge.

Keywords: *Lightning protection, portable lightning protection systems, conductive fabrics, high-current tests, tents, shelters, electroconductive textiles.*

Table of Contents

PAGE

List of figures

PAGE

List of tables

Page

List of Symbols and abbreviatures

Symbols

Symbol	Term	SI Unit
°	Degrees	
fl $km^{-2}a^{-1}$	Lightning events per square kilometer per year	
V/m	Electric field	
atm	Atmosphere	kPa
K	Kelvin	
km	Kilometer	m
m	Meter	m
%	Percent	
ms	Millisecond	
m/s	Meter per second	
μs	Microsecond	s
C/m	Coulomb per meter	
$A^2{\cdot}s$	Square ampere times second	
J/Ω	Joule per ohm	
A	Ampere	
m.a.s.l.	Meters above sea level	m
Ω	Ohm	
k Ω	Kiloohm	
W/R	Specific energy	J/Ω

Symbol	Term	SI Unit
$J \cdot \Omega^{-1}$	Joule per ohm	
V	Voltage	
i	Current in amperes	
L	Inductance	
H	Henry	
A/s	Ampere per second	
kV	Kilowatt	
kA	Kiloampere	
t	Time	s
I	Current	kA
Q_{SHORT}	Impulse charge	C
T_1 / T_2	Time parameters	µs / µs
di/dt	Average steepness	kA/µs
Q_{LONG}	Long stroke charge	C
T_{LONG}	Time parameter	s
Q_{FLASH}	Flash charge	C
kV/ Ω	Kilovolt per ohm	
$J(t)$	Current density	A/m^2
$K(t)$	Surface current denisty	A/m
r	Distance radius	m
σ	Conductivity	S/m
$E(t)$	Electric field	
s	Distance	m
S/m	Siemens per meter	
EPR	Earth potential rise	$Vpeak$

Symbol	Term	SI Unit
Ipeak	Peak value of the current	A
Hz	Frequency in Hertz	
mA	Milliamperes	
ε_r	Relative permittivity	
ε_0	Permittivity of the vacuum	
ω	Applied frequency	
μ	Magnetic permeability	
kfps	1000 frames per second	

Abbreviations

Abbreviation	Term
CG	Cloud-to-ground lightning
Cigré	*Conseil International des Grands Réseaux Électriques* (International Council on Large Electric Systems)
CPR	Cardiopulmonary arrest resuscitation
CT	Computed tomography
DIPSE	*Dirección de preservación de la integridad y seguridad del ejército de Colombia* - Directorate for the Preservation of the Integrity and Security of the Colombian Army
ECF	Electroconductive fabric
ECG or EKG	Electrocadiogram
EJC	*Ejército Nacional de Colombia* - Colombian National Army
ELAT	*Grupo de Eletricidade Atmosférica*
EMC	Research group Electromagnetic Compability of Universidad Nacional de Colombia
EMC-UN	Electromagnetic Compatibility Research Group of UNAL
EPR	Earth potential rise

Abbreviation	Term
EPSR	Electrical Power System Research Journal
FCC	U.S. Federal Communications Commission
FEA	Finite Element Analyses
FRD	Flash rate density
ICLP	International Conference on Lightning Protection
IEE/USP	Institute of Energy and Environment of the University of São Paulo
INPE	*Instituto Nacional de Pesquisas Espaciais*
IT'IS	Foundation for Research on Information Technologies in Society
LABE	*Laboratorio de Ensayos Eléctricos Industriales “Fabio Chaparro”* (Industrial Electrical Testing Laboratory “Fabio Chaparro” at Universidad Nacional de Colombia)
LEMP	Lightning electromagnetic pulse
LIC	Lightning impulse current
LICD	LIC density
LPS	Lightning protection system
MRI	Magnetic resonance imaging
NLM	U.S. National Library of Medicine
NOAA	National Oceanic and Atmospheric Administration
RT	Tolerable risk
SEM	Scanning electron microscope
SIPDA	International Symposium on Lightning Protection
U.S.A.	United States of America
UNAL	*Universidad Nacional de Colombia* (National University of Colombia)
VHP	Visible Human Project

Introduction

Natural phenomenon of lightning is spectacular, but it can be very dangerous. Their energy can let strong consequences in life, equipment and structures causing large social, natural, and financial affectations both directly and indirectly. Thousands of lightning-caused victims continue to be reported annually around the world, many of them plausible to prevent. In developing countries, the lack of adequate information about the lightning phenomenon and basic prevention measures are main aspects related to the large number of victims while in developed countries, carelessness and outdoor activities for leisure, sport and duty are the main responsible for the increasingly low mortality rates. In any case, mandatory or not, the exposition in outdoor places during thunderstorm weather accounts for a great number of injuries, many of them with fatal consequences. In Colombia, many soldiers serving in the military have been involved in lightning-related accidents and it will be show that, on a 15-year average, for the army population almost one soldier died per month, and for every four lightning-related accidents.

The interactions between lightning and living beings can produce different effects in the victim, acting in several ways according to the pathway of the lightning current, the exposition type of the body, and the strength of the electric current. Since the lightning mechanism with most deleterious effects is the earth potential rise (EPR), also known as step potential, to minimize the total risk caused by lightnings it is necessary to focus on this mechanism to reduce its effects on the health of exposed persons. In this context, this research work presents some background on lightning parameters of interest in the protection of people as well as the main known effects of its currents, to propose, develop, and test a shelter to the reduce lightning-caused risks.

The research question and objectives proposed for this research are cited below.

RESEARCH QUESTION

The purpose of this research is to study lightning injury mechanisms causing human fatalities in outdoor activities and to evaluate possible ways to reduce the risk and consequences when exposure to it is mandatory, through a development of a personal portable lightning protection system. Then, for this investigation arise the question about how to protect with light and portable equipment the lives of human beings who should be exposed to the lightning risk.

GENERAL OBJECTIVE

To analyze, design and evaluate systems, equipment or portable elements that could divert lightning currents to protect human beings, to reduce the number of fatal accidents and post-traumatic effects caused by lightning.

SPECIFIC OBJECTIVES

- To analyze existing human electric body models and compare them with some observations of physiological effects of the electrical currents produced by lightning.
- To improve the understanding of lightning caused corporal injuries, intended to assess the effects of the lightning currents flow through the human body.
- To propose and evaluate personal lightning protection equipment that could reduce the post-traumatic effects, controlling the electrical current flow to safe levels through the organism, avoiding permanent and fatal injuries caused by this phenomenon.
- Experimental validation of personal lightning protection systems.

This thesis has been structured in five main chapters. Chapter 1, Lightning phenomenon and lightning protection systems, presents some key concepts and parameters related to the lightning that can be applied to protect people against lightning currents. Moreover, related standards and guidelines are also included. Chapter 2, Effects of lightning currents on human beings, shows the known interactions between human beings and lightning currents that can result in injuries ranging from minor to severe, some resulting in permanent disability and even death. In this chapter are discussed models of human body applied to lightning interactions mechanisms. Some reports regarding lightning-cause injuries arising for the purpose of this work are presented in Chapter 3, Personal lightning protection – Case reports – Requirements, as well as the scope and requirements that a personal lightning protection system should have.

Chapter 4, Proposal of a personal lightweight and portable lightning protection system, is the core of this research and shows a brief background on electroconductive fabrics, also presenting some peer-reviewed published papers (several on conference proceedings and three in international journals) including other unpublished work regarding impulsive current tests to prove the feasibility of a proposed basic shelter model. These papers are cited throughout this document and tabulated in Chapter 4. Moreover, three projects currently closed, developed in the frame of this thesis are also listed. Cover pages of the published papers are also included as an appendix at the end of this work.

Finally, the Chapter 5, shows the conclusion and recommendations resulting from the observations and consequent results of this work.

1. Lightning phenomenon and lightning protection systems

Lightning is a natural common event around the world that can cause injury or death to living beings such as people, animals and vegetation, but it can also affect and destroy buildings, structures and equipment every year. Most of lightning injuries and fatalities occur in outdoor environments, rarely occurring inside robust buildings.

Following is presented some main aspects of the lightning phenomenon and systems devoted to protecting against dangerous lightning currents focused on people's protection.

1.1 Lightning phenomenon

Lightning maps reveal the uneven distribution of the lightning activity around the world, as shown in Figure 1-1. The images were processed from the data of Lightning Imaging Sensor (LIS) on board the NASA Tropical Rainfall Measuring Mission (TRMM) launched as payload of the Microlab-1/OrbView-1 satellite in November 1997 for ±38° latitude span. It is shown the annual average flash rate density (FRD), local hour of maximum FRD, and the month with the higher activity for the 16 years from 1998 to 2013. Figure 1-2 shows a close-up of that total lightning observations from TRMM LIS (1998-2013) for the region around Colombia where are placed three of the top-ten places with most lightning activity in the world: Lake Maracaibo – Venezuela (9.75°, –71.65°) with 233 fl km^{-2}a^{-1} is the Earth's top-ranked total lightning hotspot, Cáceres – Colombia (7.55°, –75.35°) No. 4 with 172 fl km^{-2}a^{-1} and El Tarra – Colombia (8.85°, –73.05°) No. 7 with 139 fl km^{-2}a^{-1} [1]. IEC 62858:2019 defines ground strike point density NSG as the mean number of ground strike points per square kilometer per year [2] fl km^{-2}a^{-1} herein related as FRD.

As it can be seen in lightning maps, the lightning activity is more common over land than over oceans, since intense convection occurs more frequently above the continents, mainly due to the air is heated more easily over the ground, increasing convective updrafts. Lightning activity over the oceans is about one third smaller than over land [3]. Certainly, local hour and time of the year (month of the season) have a strong effect in the lightning activity as shown in Figure 1-1 and Figure 1-2.

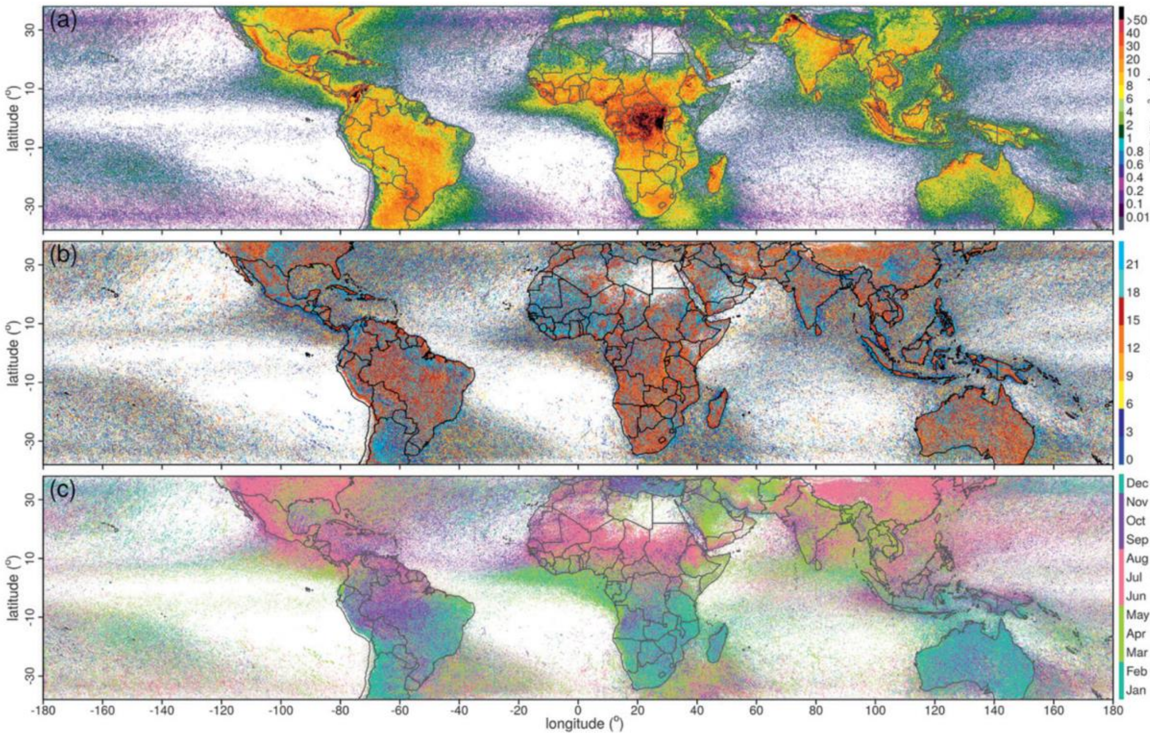


Figure 1-1. Total lightning climatology in very high horizontal resolution from 16 years (1998-2013) of TRMM LIS total lightning observations for the latitude band of ±38°: a) flash rate density FRD (flashes km^{-2}a^{-1}), b) local hour of maximum FRD, and c) month of maximum FRD. Source: [1].

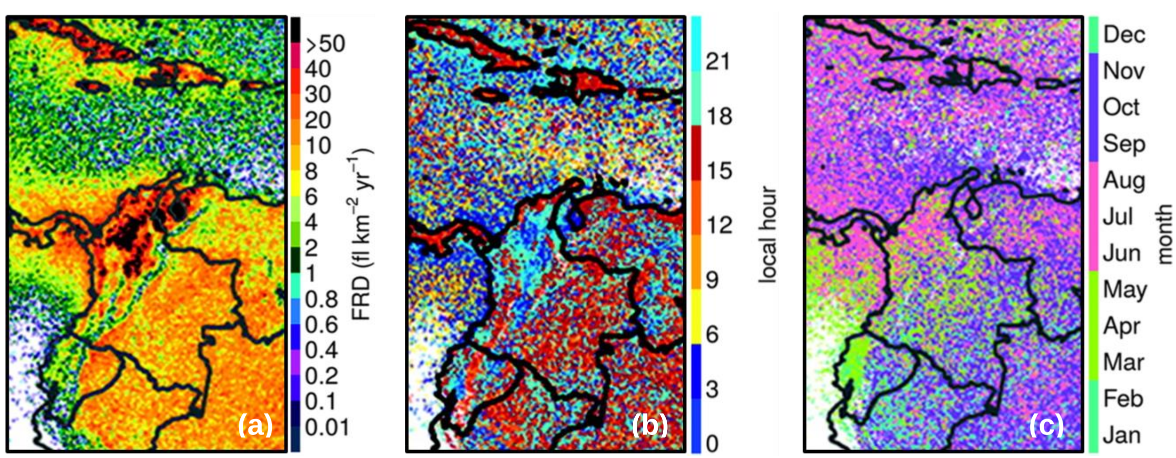


Figure 1-2. Close-up of TRMM LIS total lightning observations (1998–2013) for Colombia region in the intertropical zone: a) flash rate density FRD, b) local hour of maximum FRD, and c) month of maximum FRD. Lake Maracaibo in Venezuela (9.75°, –71.65°) with 233 fl km^{-2}a^{-1} is the Earth's top-ranked total lightning hotspot. Source: adapted from [1].

Other global lightning activity maps, such as the Vaisala of the Figure 1-3, shows also that lightning activity is less frequent as it approaches to the poles, concentrating most of the activity around the Intertropical Convergence Zone, which concords to maps of Figure 1-1.

On the other hand, Figure 1-3 map shows some regions concentrating more than 128 lightning events km^{2}a^{-1}, known as lightning hotspots. Moreover, Albrecht et al., identified that 24 of the first 30 places with the most lightning activity are close to mountainous regions, disclosing a correlation between lightning hotspots and topography [1].

Storm clouds (i.e., cumulonimbus clouds) are responsible of common lightning flashes because of the inside electric charge separation and accumulation. The most accepted theory about the in-cloud charge generation is the mechanism of collision of water particles of snow pellets and small ice crystals in the presence of super-cooled water drops [4], [5]. Lightning books, such as of Cooray, and Rakov and Uman, develops and describe clearly and deeply this and other theories about the lightning formation inside the clouds [3]–[6].

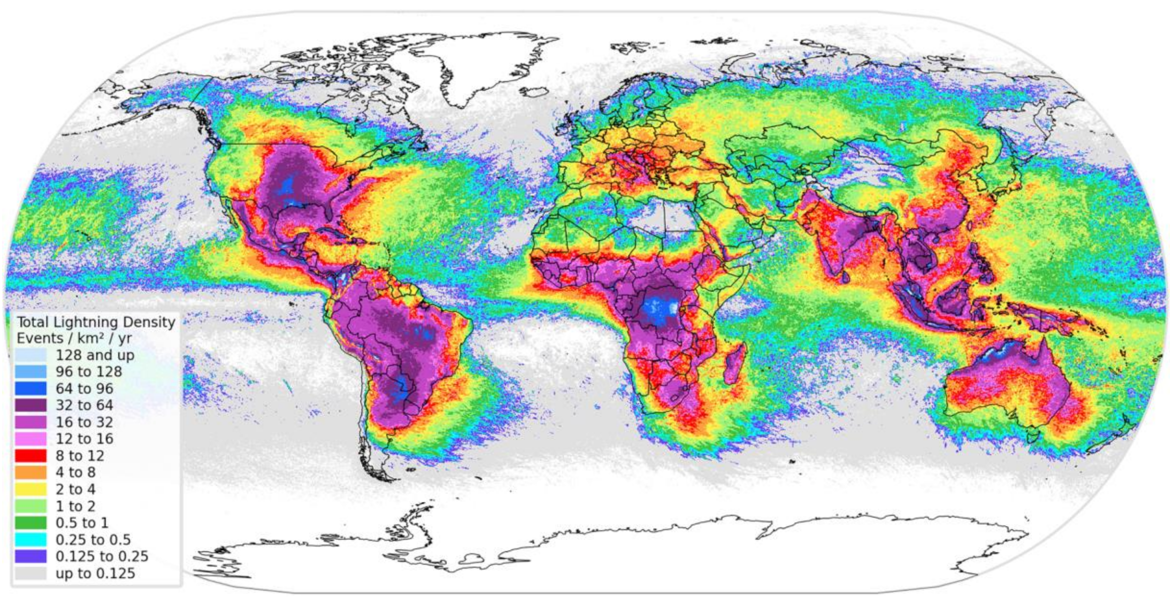


Figure 1-3. Average global total lightning density from Vaisala GLD360 network, 2016–2020. Source: Vaisala.

Air acts as an insulator until the electric field to which it is exposed exceeds the critical value of about 3×10^{-6} V/m, at temperature of 293 K and atmospheric pressure of 1 atm, which is called standard atmospheric condition. When the electric field over air exceeds the critical value, the insulating behavior changes quickly into a conducting medium, making possible the electrical current flow through it in the form of sparks [4].

Lightning is related to the physics of electrical discharges as it is a giant electrostatic discharge. Lightning flashes cannot be studied under controlled laboratory conditions. For understanding the lightning process, mechanisms of electric spark are studied in laboratory, since similarities have been observed between the small laboratory sparks and lightning discharges, both as manifestation of electricity [3]. However, some artificial lightning flashes induced by artificial means, such as rocket-triggered or tall structures, are also studied.

Lightning is a rapid high flow of electrical current from, to or inside storm clouds that equalize their regions of accumulated positive or negative charges. It can be considered as a very long electrical spark, greater than about 1 kilometer. Lightning generated in storm clouds is characterized by a length of 5 to 10 km, but can reach more than 100 km [7]. On April 29, 2020, the longest single flash was recorded, with a horizontal distance of 768 ± 8 km across the southern United States. The longest electrical sparks usually generated in the laboratory measure 1 to 3 meters, with a maximum of 10 to 20 m [7]. Lightning events occur as cloud lightning (intra-cloud, or cloud-to-cloud) or as cloud-to-ground lightning (CG). Cloud discharges are the most frequent type of lightning activity, representing about 70-75 % of the total global lightning activity [6]. The remaining 25-30 % are CG interactions that pose the greatest lightning danger to living beings.

A lightning that hits an object is referred as a "lightning strike”. The term "stroke" applies to components of cloud-to-ground discharges. Typically, lightning flashes are composed of more than one stroke. In the same flash, strokes after the “first” are referred to “subsequent”, and the number of strokes to “multiplicity”. A downward-moving process termed “leader”, and an upward-moving process termed “return stroke” compose each lightning stroke. Most of the lightning energy is transformed to produce the thunder, hot air, light, and radio waves, leaving only 1 % to 10 % of the total energy at the strike point [8]. There are four categories of lightning flashes between cloud and ground (CG): downward positive and negative flashes, and upward positive and negative flashes, as represented in Figure 1-4. A complete description of the mechanism of the lightning flash is provided in Cooray [3], and Rakov and Uman [5] between several others. Downward flashes are believed the more representative of natural lightning, and upward flashes are primarily associated more with the effect of tall artificial structures [9]. Cloud-to-ground lightnings initiated by a negatively charged, downward-propagating ‘‘leader’’, as shown in Figure 1-4 a), represent approximately 90 % of all lightning flashes that strike the ground [4], [7], connecting the positive charge center in the cloud with the surface of the earth.

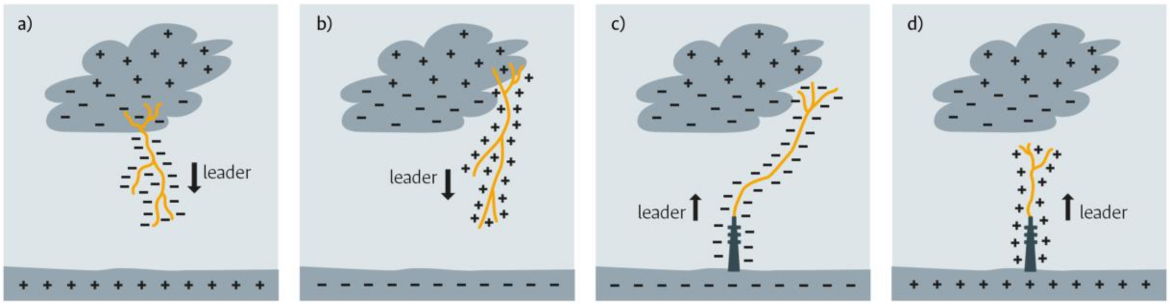


Figure 1-4. Discharge mechanisms of downward negative (a) and positive (b) lightnings, and upward negative (c) and positive (d) lightnings; Only the initial leader is shown for each type. Source: Adapted from Dehn [10].

1.2 Lightning parameters causing damage

Lightning, like any other natural weather phenomenon, is probabilistic in nature. Waveforms and amplitudes can vary considerably from one flash to another [11]. Lightning parameters have been investigated to determine characteristics and possible effects of this phenomenon. A reliable synthesis was published within CIGRE activities on the Technical Brochure TB 579 of the working Group WG C4.407 [8].

Although all the typical lightning parameters are important, four properties of the lightning current can be considered the most relevant in producing damage: (1) the peak current, (2) the maximum rate of change of current, (3) the integral of the current over time (i.e., the charge transferred), and (4) the integral of the current squared over time, the so-called action integral (sometimes also known as specific energy) [4]–[7]. These parameters are commonly related to the first return stroke and subsequent strokes, with the current peak value commonly referred as the most important parameter to engineering applications [6], [7], [12]. On the other hand, continuing currents produced as long duration currents when the return stroke current does not reach zero but continue to flow at a low level for some hundreds of milliseconds [3] can cause forest fires and acute damage in living beings [7].

Although positive lightnings to ground has higher current levels than negative ones and most deleterious effects, the latter are much more frequent (about 90 %) and therefore its data more relevant for this research. Some typical parameters of negative flashes are presented in Table 1-1. However, according to some lightning studies carry out in some places of Colombia, the distribution of polarity flashes for this country is on average 67 % for negative and 33 % for positive ones, showing an uneven distribution of their values according to the geographic site. From a study of 69 electric field signal measurements of lightning flashes carried out in Bogotá - Colombia, only one signal was found associated to positive polarity lightning, this is 1.5 % [13]. It has been suggested that the median value of the peak current is more intense for intertropical zones, as shown in Table 1-2 [12], but the data should be taken with care due the differences in measuring methods and times [14].

Table 1-1. Typical parameters of negative ground lightning flashes. Source: Adapted from Cooray [4] with data from Berger et al [9].

Parameter	Typical value or range
Duration of lightning flash	200 – 300 ms
Number of return strokes per flash	3 – 4
Time interval between strokes	40 – 60 ms
Percentage of flashes with single strokes	20 %
Speed of stepped leaders	3×10^5 m/s
Time interval between steps of stepped leaders	10 – 100 µs
The charge per unit length on the stepped leader (close to ground end)	0.001 C/m
Peak current in first return stroke	30 kA
Rise time of current of first return strokes	5 µs
Rate of change of current of first return strokes	10 – 20 kA/µs
Action integral for negative first strokes (W/R)	6×10^4 $A^2 \cdot s$ (or J/Ω)
Action integral for negative subsequent strokes (W/R)	6×10^3 $A^2 \cdot s$ (or J/Ω)
Charge associated with first return stroke	5 C
Speed of dart leaders	10^7 m/s
Length of dart leader	10 – 70 m
Charge on dart leader	1 C
Peak current of subsequent strokes	12 kA
Rise time of current of subsequent strokes	0.5 µs
Rate of change of current of subsequent strokes	50 – 100 kA/µs
Charge associated with subsequent strokes	1 C
Percentage of flashes with continuing currents	30 – 50 %
Duration of continuing currents	100 ms
Amplitude of continuing currents	100 – 200 A
Peak current of M-components	100 – 200 A
Rise time of M-component current	400 µs
Duration of M-component current	2 ms

Table 1-2. Median values of the return stroke peak current taken from lightning research in some countries of the world. Source: data from NTC 4552 [12].

Country	Median value (kA)
United States of America	23
Swiss	30
Sweden	30
Poland	31
Malaysia	36
Brazil (1)	43
Zimbabwe (formerly Rhodesia)	42
Colombia (2)	43

(1) Morro do Cachimbo, Minas Gerais, Brazil 1996.

(2) Estimated value from electric field measurements at less than 100 km.

In Colombia, the median value of lightning peak currents was estimated from electric field measurements [12], while in Brazil, direct measurements were done at a lightning station located on the top of Morro do Cachimbo mountain at 1430 m.a.s.l., through a 60 m high instrumented tower [15].

Figure 1-5 shows the cumulative distribution probability of negative return stroke currents for some countries placed in temperate zones (CIGRE, 1979) and in intertropical zones (Colombia, Brazil, Malaysia, and former Rhodesia currently Zimbabwe). NTC 4552 states that for Colombia and Brazil, the 50 % lightning current peak value is about 43 kA [10].

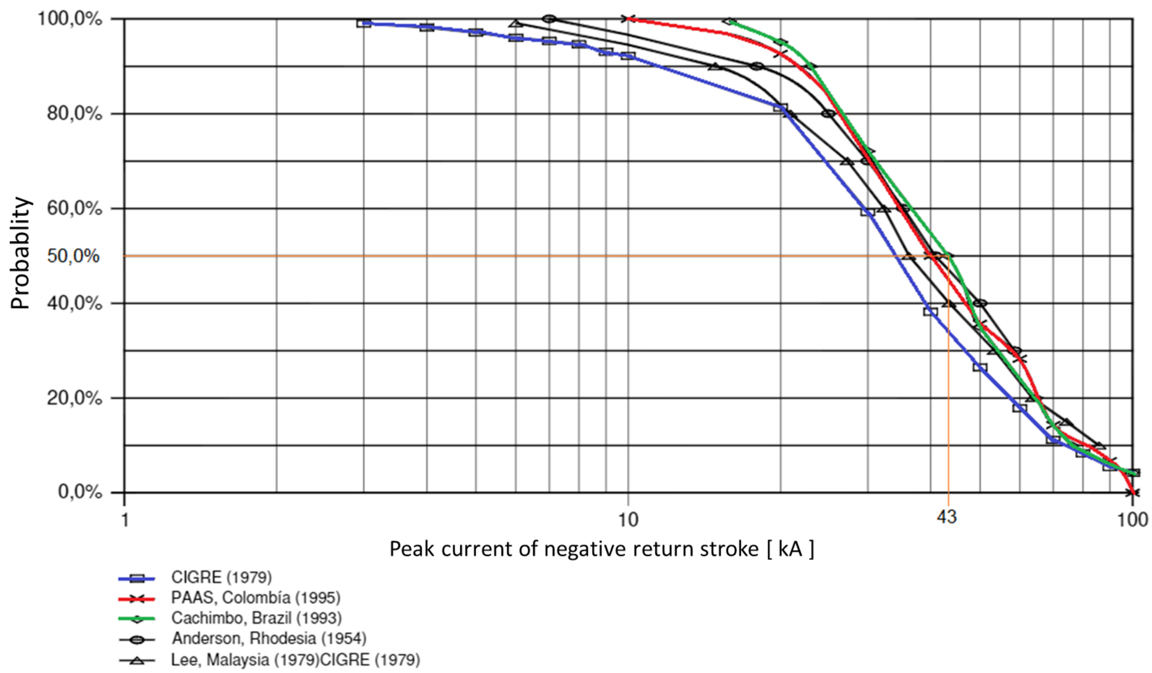


Figure 1-5. Cumulative distribution probability of negative return stroke currents for countries placed in temperate zones (Cigré) and in intertropical zone. Source: Adapted from NTC4552:2008 [12].

The lightning damage that someone or something suffers depends on the parameters of the lightning discharge, the properties of the object or victim [5], and the characteristics of the impact site.

Lightning strikes will often cause some damage that cannot be predicted before a physical simulation, using high current tests in the laboratory. In the aerospace industry, some of the studies on direct effects of lightning strikes over composite materials show the level of damage, loss of mechanical properties and three modes of damage, namely: fiber damage by reduction of length/diameter, resin deterioration by vaporization, and delamination by separation of composite layers. Each of these damage modes is linked to a lightning simulation parameter: fiber damage to peak current of lightning strike, resin deterioration area to electrical charge, and delamination projection area to the action integral of the waveform [16].

1.2.1 Action integral

In a conductor subjected to an electrical current, heat is generated by its resistive impedance due to Joule heating, also known as ohmic heating or Joule's first law. If the current is high enough, the heat generated by the conductor itself could melt it. In lightning research, the action integral, also called specific energy (or even prospective energy in [6]), relates energy per unit resistance at the lightning attachment point as "energy that would be dissipated in a 1 Ω resistor if the lightning current were to flow through it" or injected [6]. Therefore, the action integral W/R is related to amount of energy dissipated in a resistance,

$$\frac{W}{R} = \int_0^{t1} I^2\,(t)dt \qquad \text{Eq. 1}$$

The integral limits 0 and $t1$ refers to the duration of the event or return stroke. The action integral is measured in $A^2 \cdot s$ or in $J \cdot \Omega^{-1}$ [3], [5]. In lightning protection applications, suitable earthing system are needed to prevent hazard to life. For these systems, lightning damages due to thermal effects is avoided selecting proper conductors, considering the highest values from the statistical distribution of the action integral determined by the previous Eq. 1 [3], [4], [17]. If energy is known, the increase in temperature of the object under study can be calculated. Heating, melting, or even explosion of resistive materials and insulators subjected to lightning currents are related to the value of the action integral [5]. Note that the given value in Table 1-1 for W/R negative first return strokes of 6×10^4 $A^2 \cdot s$ (or J/Ω) corresponds to the average percentage of cases that exceed 50 % for 101 strokes, data taken by Berger et al. (1975), shown by Cigré WG C4.407 [8] in its Table 3.5.

To assess the maximum risk due to temperature rise, calculations often adopt fixed values specified for the action integral, which are specified in the standards [18]. For example, 10 MJ/Ω is stated for the specific energy in Lightning Protection Level I (LPL I) according to the IEC 62305-1:2010 [19].

On the other hand, on material-epoxy composite panels subjected to simulated lightning impulses, a correlation between the type of damage and the applied current parameters has been presented [16], [20], [21]. Action integral has also widely used to correlate data during studies of exploding wires [22].

1.2.2 Inductive impedance

Objects with an inductive impedance, such as wires and conductive materials, the peak voltage V produced as result of a transient current through it will be proportional to the maximum rate of change of the current di/dt as

$$V = L\, di/dt \qquad \text{Eq. 2}$$

where L is the inductance in henries of the object, i the current in amperes, and t the time. In a lightning flash, the current could be direct or induced. For instance, if 1 m of conductive material with an inductance L of 10^{-6} H carries a typical lightning current with rate of-rise of $di/dt = 10^{11}$ A/s, across of that material can be generated 100 kV. In consequence, a fraction of a typical peak lightning current can cause severe damage in equipment or living beings by the generation of inductive voltage differences [23].

1.3 Lightning protection systems

Lightning flash to earth is a very high energy phenomenon, source of harm that may be hazardous to living beings, structures, lines, and equipment [19], [24]. Lightning cannot be avoided because they are probabilistic natural phenomena but reducing the risk their harmful and deleterious effects can be reduced. According to international standard IEC 62305 “Protection against lightning – All parts”, the scope of a lightning protection system (LPS) is to protect structures and equipment against direct lightning strikes and from eventual fires and consequences of lightning currents, not necessarily causing ignition such as surges in power lines. The lightning damages can range from catastrophic to minor. Lightning protection measures must be implemented if required by local regulations or any other directives.

Even though lightning protection is needed in buildings, structures, and equipment to avoid financial losses, the not always disclosed main objective of a LPS is primarily to protect people's lives against lightning effects. Serious consequences, traumata or death can occur when lightning strikes a place with people (or living beings), even more in gathering places such as markets, schools, hospitals, and meeting rooms. To reduce the risk, it is necessary that all endangered structures are permanently equipped with effective protection systems against lightning. Table 1-3 present a relationship between source of damage, type of damage, cause, and type of loss, according to information given in IEC62305-1.

Table 1-3. Relationship between source of damage, type, cause, and type of loss due to lightning strikes. Source: adapted from data of IEC62305-1 [19].

Source of damage	Type of damage	Cause	Type of loss
S1: Strike to structure	D1: injury to living beings by electric shock	step and touch voltages resulting from resistive and inductive coupling	L1: human life L4: economic value
	D2: physical damage such as - immediate mechanical damage - fire, explosion, chemical release	current resulting in ohmic heating of conductors, or due to the charge resulting in arc erosion (melting) overvoltage resulting from resistive and inductive coupling and to passage of part of the lightning currents	L1: human life L2: service to public L3: cultural heritage L4: economic value
	D3: failure of internal systems	lightning electromagnetic pulse LEMP	L1: human life L2: service to public L4: economic value
S2: Near the structure	D3: failure of internal systems	lightning electromagnetic pulse LEMP	L1: human life L2: service to public L4: economic value
S3: To lines connected to the structure	D1: injury to living beings by electric shock	touch voltages inside the structure caused by lightning currents transmitted through the connected line	L1: human life L4: economic value
	D2: physical damage such as fire or explosion	sparks due to overvoltage and lightning currents transmitted through the connected line	L1: human life L2: service to public L3: cultural heritage L4: economic value
	D3: failure of internal systems	overvoltage appearing on connected lines and transmitted to the structure	L1: human life L2: service to public L4: economic value
S4: Near the lines connected to structure	D3: failure of internal systems	overvoltage induced on connected lines and transmitted to the structure by LEMP	L1: human life L2: service to public L4: economic value

Prevention is always the best measure of personal lightning protection. However, the exposition to lightning risk is unavoidable for many human activities [25], [26], as well as for buildings and structures that are exposed to lightning strikes especially in places with high lightning activity. To reduce the risk and effects of lightning currents, lightning protection systems have been developed for the objects to be protected, as well as methods, standards, and guidelines. Currently, regard to human and living being's protection against lightning, there are very few technical references or standards, particularly when are outside of buildings. International lightning safety standards are intended to protect structures and often do not consider the effects of currents on people and living beings. To date, there are not standards on methods or use of equipment to reduce the risks of lightning for humans exposed to them. About this, only the technical report IEC/TR 62713 “Safety procedures for reduction of risk outside a structure” emerges with an outlook to prevention of lightning strikes in people with some information about actions that could be taken to reduce the risk [25], [26].

1.3.1 Basic principles and usual methods of lightning protection

To protect against lightning effects the living beings, structures, and equipment, lightning protection systems (LPS) are used. Usually, LPS consists of both external and internal lightning protection systems for protection to reduce physical damage and life hazard [19].

An effective external LPS are intended to: 1- intercept or catch the lightning currents, 2- conduct, and 3- disperse them safely into the ground [19], [27], [28]. Figure 1-6 shows a representation with the parts of a lightning protection system. Since lightning currents could reach up to some hundreds of kiloamperes, materials and components of LPS should be able to effectively carry these currents. The function of the internal LPS is to prevent dangerous sparking within the structure, using equipotential bonding or a separation distance between the LPS components and other electrically conducting elements internal to the structure [19]. A complete LPS must be an effective protection of structures against physical damage and to avoid injury to living beings caused by touch and step voltages. Therefore, its main objective is to reduce the flow of dangerous currents through bodies [28] and the overvoltages that they could cause.

The part of an external LPS that intercepts the lightning currents is known as air terminals, all of which form one unit of the system. Its dimensions and materials should be adequate to prevent it from exploding or vaporizing when struck by a lightning with very large currents. The air terminals dimensions are specified in the international lightning protection standard [27], [29]. The currents intercepted by air terminals must be safely transported to the ground by the LPS across the called down conductors. The placement of down conductors must consider that the current flow along them could rise a high potential, depending on the self-inductance and the impedance at the grounding point, and there should be no metal structures nearby of these down conductors as a side flash could be generated [29]. When nearby metal structures cannot be avoided, they must be joined by connecting to the down conductors to potential equalization. Reducing the impedance at the ground end of the down conductors reduce the probability of occurrence of side flashes. On the other hand, the current flow along down conductors generate magnetic fields varying in time. The interaction of these magnetic fields can generate induced voltages with any other conducting loops in the vicinity, perturbing or even damaging electronic equipment around. Additionally, the induced voltages could generate small discharges or sparks between small gaps in conductors. Then, down conductors should be arranged to minimize these undesirable voltages, for example, by placing them symmetrically (at least two) around the structure to divide the current and minimize the magnetic field inside (see Figure 1-6). All air terminals and down conductors should be connected appropriately to each other and to the grounding system. Several down conductors around an object to protect it, establish the Faraday cage topology for lightning protection [29].

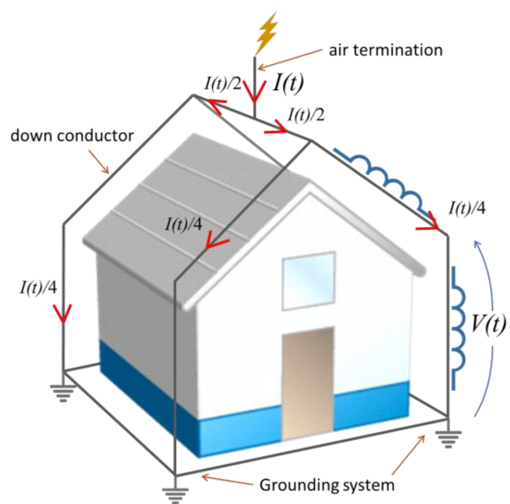


Figure 1-6. Parts of an external lightning protection system (LPS) formed by air terminations, down conductors, and the grounding system with a ring conductor. Source: author.

The Faraday´s shield

The best procedure to protect a building or an object from lightning strikes is applying the Faraday cage concept. Ideal protection from both the currents and the electromagnetic field of lightning is inside of an enclosed metal structure with no holes, openings, or apertures, including that associated with through penetrations by conductors, tubes, or pipes such as those of power or communication signals. This type of closed conducting structure is known as electrodynamic Faraday cage, Faraday shield, or most commonly Faraday Cage.

Although this conductive enclosure concept is not practical since most structures need penetrations or windows, a systematic approach can be used considering that electromagnetic fields and time-varying currents are strongly attenuated when propagating inside closed conducting cages [7]. Even though it is not practical to completely enclose a building with a complete metal cage, and is not really common [3], a practical Faraday cage can be achieved using a conductive mesh, known as the mesh method [6], moreover when several surrounding down-conductors are used in the LPS.

The Faraday shield is a protection against electromagnetic fields that can be used against lightning indirect effects when very sensitive equipment needs to be protected against lightning electromagnetic fields induced by near strikes. In this work the use of a protective mesh will be shown as a protection measure against lightning currents.

Protection measures

To minimize the risk and losses due to lightning, protection measures are required. To reduce the risk according to the type of damage can include the protection measures listed and described in Table 1-4 that form the complete lightning protection. The most suitable measures of protection shall be selected by the designer and the owner of the structure to be protected. Such measures must consider the type and amount of each damage, the technical and economic aspects of the protection measures, and the results of a risk assessment [6], [19].

Table 1-4. Possible protection measures depending on the damage type. Source: from data of [19].

type / measure	D1: Injury of living beings by electric shock	D2: physical damage	D3: failure of electrical and electronic systems
1	adequate insulation of exposed conductive parts	air-termination system	earthing and bonding measures
2	equipotentialization by means of a meshed earthing system	down-conductor system	magnetic shielding
3	physical restrictions and warning notices	earth-termination system	line routing
4	lightning equipotential bonding (EB)	lightning equipotential bonding (EB)	isolating interfaces
5	-	electrical insulation (and hence separation distance) against the external LPS	coordinated surge protective device system

The entire IEC 62305 standard presents methodologies to ensure risk reduction and avoid physical damage or life hazards and particularly IEC 62305-2 gives the criteria for risk assessment and guidelines for selection of the most suitable protection measures, while IEC62305-3 provides orientation on the use of materials, components, and equipment to conform a LPS. These materials can be considerably heavy, large or bulk in most of the cases making it difficult to have an appropriate LPS in some places such as outdoor, faraway, backcountry or not easily accessible locations, where it is very difficult the use of such materials, leaving people activities in that situations exposed permanently to a catastrophic risk [30].

In lightning protection, the safety level class of a lightning protection system (LPS) is designed according to different protection levels related to lightning protection levels (LPL) [4], [19], [27]. Table 1-5 reports the maximum values for the various lightning parameters according to the level of lightning protection. The LPL corresponds to the class of the LPS.

Table 1-5. Maximum values for the four lightning protection levels. Source: taken from [19].

First positive impulse			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Peak current	I	kA	200	150	100	
Impulse charge	Q_{SHORT}	C	100	75	50	
Specific energy	W/R	MJ/Ω	10	5.6	2.5	
Time parameters	T_1 / T_2	µs / µs	10 / 350			
First negative impulse*			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	
Peak current	I	kA	100	75	50	
Average steepness	di/dt	kA/ µs	100	75	50	
Time parameters	T_1 / T_2	µs / µs	1 /200			
Subsequent impulse			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Peak current	I	kA	50	37.5	25	
Average steepness	di/dt	kA/ µs	200	150	100	
Time parameters	T_1 / T_2	µs / µs	0.25 / 100			
Long stroke			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Long stroke charge	Q_{LONG}	C	200	150	100	
Time parameters	T_{LONG}	s	0.5			
Flash			**LPL**			
Current parameters	**Symbol**	**Unit**	**I**	**II**	**III**	**IV**
Flash charge	Q_{FLASH}	C	300	225	150	

The procedures used widely to protect structures from lightning flashes are conceived to place air-terminals and to intercept adequately the lightning currents by the attaching process of the down-coming stepped leader and the upward connecting leaders. These methods are the protection angle (or cone of protection), the electro-geometric, the rolling sphere, and the mesh method. In these approaches some assumptions are taken which are generally accepted to simplify the design process of the lightning protection system. There is a vast technical, scientific, and commercial literature that develops these topics clearly and very well [6]–[8], [10], [29], [31]. It is important not to lose sight of the fact that protections should also act to protect against induced lightning currents such as produced by power lines or metallic fences struck by lightning currents.

1.3.2 Standards and guidelines related to lightning

Lightning protection systems are considered the most useful measure against the risk caused by lightning, which is why norms, standards, and guidelines have been developed and adopted in many countries around the world. In Colombia, the Technical Regulations for Electrical Installations (*Reglamento Técnico para las Instalaciones Eléctricas* – RETIE) has included the “Lightning protection requirements” in its article 16 of the latest version of 2015, which consider to follow and apply the recommendations of the international standard series IEC 62305 and the Colombian standard NTC 4552 [32].

The main purpose of lightning protection systems is primarily to protect people's lives against lightning currents. Standards such as the risk management document IEC62305-2, used to calculate the potential risk against lightning to living beings as well as financial losses in conventional structures, are ultimately intended to protect lives and properties by reducing exposure to risk. The International classification of standards related to lightning protection are identified as ICS 91.120.40 (ISO 91.120 Protection of and in buildings – 40 Lightning protection). The most relevant standards and guidelines related to lightning protection are listed below in Table 1-6 , some of which have been introduced throughout this chapter. The most relevant international standards related to lightning protection and its effects are the set of IEC 62305, the set of IEC 62561, IEEE Std 1410, IEEE 998, and NFPA 780 which include important definitions and criteria to be used in lightning protection systems. Local standards most relevant to lightning protection for Colombia and Brazil are the set of NTC 4552 and the set of NBR5419. NTC 4552 is a modified standard based in the IEC 62305, as also the NBR5419 but the latter was supplemented with other elements and local research.

Table 1-6. Standards, guidelines, and norms related to lightning and lightning protection. Source: IEC webstore [33], IEEE SA [34], ABNT Brazil [35], and ICONTEC Colombia [36].

Standard or guideline	Title	Brief description or reference
IEC 62305-1:2010	Protection against lightning - Part 1: General principles	Provides general principles to be followed for protection of structures against lightning, including their installations and contents, as well as persons [19]
IEC 62305-2:2010	Protection against lightning - Part 2: Risk management	Applicable to risk assessment for a structure due to lightning flashes to earth. Its purpose is to provide a procedure for the evaluation of such a risk. Once an upper tolerable limit for the risk has been selected, this procedure allows the selection of appropriate protection measures to be adopted to reduce the risk to or below the tolerable limit [24]
IEC 62305-3:2010	Protection against lightning - Part 3: Physical damage to structures and life hazard	Provides the requirements for protection of a structure against physical damage by means of a lightning protection system (LPS), and for protection against injury to living beings due to touch and step voltages in the vicinity of an LPS (see IEC 62305-1) [27]
IEC 62305-4:2010	Protection against lightning - Part 4: Electrical and electronic systems within structures	provides information for the design, installation, inspection, maintenance and testing of electrical and electronic system protection (SPM) to reduce the risk of permanent failures due to lightning electromagnetic impulse (LEMP) within a structure [37]
IEC 60479-1:2018	Effects of current on human beings and livestock - Part 1: General aspects	provides basic guidance on the effects of shock current on human beings and livestock. It is not intended for use by manufacturers or certification bodies
IEC 60479-2:2019	Effects of current on human beings and livestock - Part 2: Special aspects	describes the effects on the human body when a sinusoidal alternating current in the frequency range above 100 Hz passes through it
IEC TR 60479-3:1998	Effects of current on human beings and livestock - Part 3: Effects of currents passing through the body of livestock (**withdrawn**, replaced by IEC 60479-1:2018)	**Replaced** by IEC 60479-1:2018. Provides basic guidance on the effects of electric currents on cattle for use in the establishment of electrical safety requirements
IEC TR 60479-4:2020	Effects of current on human beings and livestock - Part 4: Effects of lightning strokes	shows the differences of effects on human beings and livestock due to lightning strokes versus those effects of electric shocks derived from electrical systems. Includes worldwide lightning occurrences and climatic effects, direct or indirect related effects to lightning injuries to the human body, and some safety procedures

Standard or guideline	Title	Brief description or reference
IEC TR 60479-5:2007	Effects of current on human beings and livestock - Part 5: Touch voltage threshold values for physiological effects	provides touch voltage-duration combination thresholds relate to specific environmental and contact conditions that determine body impedance for some current pathways
IEC 62561-1:2017	Lightning protection system components (LPSC) - Part 1: Requirements for connection components	specifies the requirements and tests for metallic connection components that form part of a lightning protection system (LPS) [33]
IEC 62561-2:2018	Lightning protection system components (LPSC) - Part 2: Requirements for conductors and earth electrodes	specifies the requirements and tests for metallic conductors (other than "natural" conductors) that form part of the air-termination and down-conductor systems, and metallic earth electrodes that form part of the earth-termination system
IEC 62561-3:2017	Lightning protection system components (LPSC) - Part 3: Requirements for isolating spark gaps (ISG)	specifies the requirements and tests for isolating spark gaps (ISG) for lightning protection systems
IEC 62561-4:2017	Lightning protection system components (LPSC) - Part 4: Requirements for conductor fasteners	deals with the requirements and tests for metallic and non-metallic conductor fasteners that are used to retain and support the air-termination, down-conductor and earth-termination systems
IEC 62561-5:2017	Lightning protection system components (LPSC) - Part 5: Requirements for earth electrode inspection housings and earth electrode seals	specifies the requirements and tests for earth electrode inspection housings installed in the earth and for earth electrode seals
IEC 62561-6:2018	Lightning protection system components (LPSC) - Part 6: Requirements for lightning strike counters (LSC)	specifies the requirements and tests for devices intended to count the number of lightning strikes based on the current flowing in a conductor
IEC 62561-7:2018	Lightning protection system components (LPSC) - Part 7: Requirements for earthing enhancing compounds	specifies the requirements and tests for earthing enhancing compounds producing low resistance of an earth termination system
IEC TS 62561-8:2018	Lightning protection system components (LPSC) - Part 8: Requirements for components for isolated LPS	specifies the requirements and tests for insulating stand-offs, used in conjunction with an air-termination system and down-conductors with the aim of maintaining the proper separation distance, and the requirements and tests for insulating down-conductors, including their specific fasteners, able to reduce the separation distance
IEC TR 62713:2013	Safety procedures for reduction of risk outside a structure	It is not a standard but a technical report with several advices and procedures against risk. It should be noted that so far there are no means to avoid lightning. However, by following some elementary

Standard or guideline	Title	Brief description or reference
		rules, people can be protected against its deleterious effects
IEC 62793:2020	Protection against lightning - Thunderstorm warning systems	describes the characteristics of thunderstorm warning systems (TWSs) to implement lightning hazard preventive measures
IEC 61643-11:2011	Low-voltage surge protective devices - Part 11: Surge protective devices connected to low-voltage power systems - Requirements and test methods	applicable to devices for surge protection against indirect and direct effects of lightning or other transient overvoltages
IEC 62858:2019	Lightning density based on lightning location systems (LLS) - General principles	introduces and discusses all necessary measures to make reliable and homogeneous the values of lightning ground flash density NG, and ground strike point density NSG, obtained from lightning location systems (LLSs) in various countries. Only parameters that are relevant to risk assessment are considered
IEEE Std 1410-2010	IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines	factors that contribute to lightning-caused faults on the line insulation of overhead distribution lines and suggested improvements to existing and new constructions are identified in this guide
IEEE 998-1996	IEEE Guide for Direct Lightning Stroke Shielding of Substations	Design information for the methods historically and typically applied by substation designers to minimize direct lightning strokes to equipment and buswork within substations is provided. Two approaches, the classical empirical method and the electrogeometric model, are presented in detail
SAE ARP 5412:2013	Aircraft Lightning Environment and Related Test Waveforms (Aerospace Recommended Practice – ARP)	the environment and test waveforms defined in this SAE Aerospace Recommended Practice (ARP) account for the best lightning data and analysis currently available. The quantified environment and levels herein represent the minimum currently required by certifying authorities, consistent with the approach applied in related lightning documents
IEC 60060-1:2010	High-voltage test techniques - Part 1: General definitions and test requirements	applies to dielectric tests with alternating voltage; dielectric tests with direct voltage; dielectric tests with impulse voltage and dielectric tests with combinations of the above. This document is applicable to tests on equipment having its highest voltage for equipment Um above 1 kV
IEC 60060-2:2010	High-voltage test techniques - Part 2: Measuring systems	applicable to complete measuring systems, and to their components, used for the measurement of high voltages during laboratory and factory tests with direct

Standard or guideline	Title	Brief description or reference
		voltage, alternating voltage and lightning and switching impulse voltages
IEC 60060-3:2006	High-voltage test techniques - Part 3: Definitions and requirements for on-site testing	Applicable to on-site test voltages and in-service stresses: direct voltage, alternating voltage, lightning impulse voltage of aperiodic or oscillating shape: switching impulse voltage of aperiodic or oscillating shape
NFPA 780 2020	Standard for the Installation of Lightning Protection Systems, 2011 Edition	provides lightning protection system installation requirements to safeguard people and property from fire risk and related hazards associated with lightning exposure
IEEE Std 4-2013	Standard for high-voltage testing techniques	Standard methods and basic techniques for high-voltage testing applicable to all types of apparatus for alternating voltages, direct voltages, lightning impulse voltages, switching impulse voltages, and impulse currents are established in this standard
IEEE Std 80 - 2013	IEEE Guide for safety in AC substation grounding	This guide is primarily concerned with outdoor ac substations. These include distribution, transmission, and generating plant substations
IEEE Std 1584-2013	IEEE Guide for performing arc-flash hazard calculations	This guide provides mathematical models for designers and facility operators to apply in determining the arc-flash hazard distance and the incident energy to which workers could be exposed during their work on or near electrical equipment
IEEE Std 100-2000 7th edition	The authoritative dictionary of IEEE Standard terms	It establishes an authoritative common language that sets common technical criteria
IEEE Std 539-2020	IEEE Standard definitions for terms relating to corona and field effects of overhead power lines	Definitions and usage of terms used in the measurement and analysis of corona and field effects of overhead power lines are presented in this standard
IEEE Std 1048-2016 IEEE Std 1048a-2021	IEEE Guide for protective grounding of power lines	Guidelines are provided for Temporary Protective Grounding (TPG) of electric power lines to assist in protection of workers from voltages and currents that might develop at a de-energized worksite during maintenance of ac overhead and underground, transmission and distribution lines, cables, and equipment
IEEE 142-2007	IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems	The advantages and disadvantages of grounded vs. ungrounded systems are discussed. Methods of protecting structures against the effects of lightning are also covered

Standard or guideline	Title	Brief description or reference
FAA-STD-019e 2005	Lightning and surge protection, grounding, bonding, and shielding requirements for facilities and electronic equipment	The requirements of this standard provide a systematic approach to minimize electrical hazards to personnel, electromagnetic interference and damage to facilities and electronic equipment from lightning, transients, ESD, and power faults
Local and regional standards		
NTC 4120:1997 Colombia	Efectos de la corriente sobre los seres humanos y los animales domésticos. Parte 1. Aspectos generales (Effects of current on human beings and livestock. Part 1. General aspects, former IEC 479-1)	It is an equivalent standard of the former international standard IEC 471-1:1987 (currently IEC 60479-1:2018)
NTC 4552-1:2008 Colombia	Protección contra descargas eléctricas atmosféricas (rayos). Parte 1: Principios generales (IEC 62305-1:2006 Modified).	It is a modified standard based on the international standard IEC 62305-1:2006
NTC 4552-2:2008 Colombia	Protección contra descargas eléctricas atmosféricas (rayos). Parte 2: Manejo del riesgo (IEC 62305-2:2006 Modified).	It is a modified standard based on the international standard IEC 62305-2:2006
NTC 4552-3:2008 Colombia	Protección contra descargas eléctricas atmosféricas (rayos). Parte 3: Daños físicos a estructuras y amenazas a la vida (IEC 62305-3:2006 Modified).	It is a modified standard based on the international standard IEC 62305-3:2006
NTC 4591:2013 Colombia	Técnicas de ensayo a alta tensión. Definiciones generales y requisitos de ensayo (IEC 60060-1: 2010).	It is an equivalent standard of the international standard IEC 60060-1:2010
NBR5419-1:2015 Brazil	Proteção contra descargas atmosféricas - Parte 1: Princípios Gerais	Protection against lightning - Part 1: General principles
NBR5419-2:2015 Brazil	Proteção contra descargas atmosféricas - Parte 2: Gerenciamento de risco	Protection against lightning - Part 2: Risk management
NBR5419-3:2015 Brazil	Proteção contra descargas atmosféricas - Parte 3: Danos físicos a estruturas e perigos à vida	Protection against lightning - Part 3: Physical damage to structures and life hazard
NBR5419-3:2015 Brazil	Proteção contra descargas atmosféricas - Parte 4: Sistemas elétricos e eletrônicos internos na estrutura	Protection against lightning - Part 4: Electrical and electronic systems within structures
NBR6938:1981 Brazil	Técnicas de Ensaios Elétricos de Alta Tensão - Guia De Aplicação Para Dispositivos De Medição (**withdrawn**)	High-voltage test techniques – Guide to application for measuring devices. **Related** to NBRIEC 60060-1 and NBRIEC 60060-2
NBRIEC 60060-1:2013 Brazil	Técnicas de Ensaios Elétricos de Alta Tensão - Parte 1: Definições Gerais e Requisitos de Ensaio	High-voltage test techniques - Part 1: General definitions and test requirements. Equivalent to NBRIEC 60060-1:2010
NBRIEC 60060-2:2016 Brazil	Técnicas de Ensaios Elétricos de Alta Tensão - Parte 2: Sistemas de medição	High-voltage test techniques - Part 2: Measuring systems. Equivalent to NBRIEC 60060-2:2010

People can be protected against lightning deleterious effects following some basic procedures. Although the technical report IEC / TR 62713: 2013 (Safety procedures for reduction of risk outside a structure), presents lightning to the non-specialists in lightning protection, it points out some recommendable actions in the presence of electrical storms, as well as lightning protection measures to contribute to the prevention of lightning injuries and damages, even though there are currently no means to avoid lightning strikes. Concepts related to personal lightning protection will be discussed in the next chapter.

1.4 Concluding remarks

In this chapter some basic concepts and definitions about the phenomenon of lightning and lightning protection systems (LPS) were introduced. It was shown the uneven distribution of lightning activity determined by the mean number of ground strike points per square kilometer per year over the world and how some areas have an increased activity along the time. That activity is important to be considered in the design of lightning protections as also the lightning parameters that can cause damage. These parameters are mainly the peak current, the maximum rate of change of current, the integral of the current over time or charge transferred, and the integral of the current squared over time or action integral, concepts that will be use in following sections. LPS are intended to intercept, conduct, and disperse safely into the ground the hazardous lightning currents. The Faraday shielding concept serves as the basis for safe current diversion methods that will be used to the development of this work. To minimize the economical and life losses, the international standards and guidelines give guidance about principles to be followed for protection of structures against lightning, including their installations and contents, as well as persons.

Although a risk assessment is a tool for determining the need and extent of protective measures that may be required according to IEC 62305, as will be discussed later, damage to people and loss of life may be considered unacceptable from the very beginning of any study. Therefore, any measures taken to reduce the risk should always be considered.

2. Effects of lightning currents on human beings

Technical reports show lightning-related mortality ranging from as high as 30 % to as low as 5 %. Despite these varying rates, lightning remains a real hazard during outdoor activities, mainly in places with increased risk due to its high lightning activity [38], [39]. Most of the lightning-caused fatalities and permanent injuries occurs in open outdoor areas. This is true, but in the developed world for most of lightning injuries reported. For many reasons, in developing countries this may not be true [40]. What is always true is that lightning currents can have deleterious effects on the people, animals, and other living beings when it crosses through their bodies.

This chapter will present information on the effects of lightning currents on the body, the hazards and risk of direct and indirect lightning currents, the coupling mechanisms between lightning and victims, and some outlook about models of the human body that could be applied for research on lightning effects and protection, all from an engineering point of view avoiding the use of highly specialized medical vocabulary or explaining it where necessary.

2.1 Effects of lightning currents and damage to people

Considering the lightning currents and the impedance of living beings bodies with an electrical linear behavior, then, these must obey the Ohm´s law. The body impedance values depend on several factors such as the current path, touch voltage, frequency of the current, duration of the current flow, moisture of the skin, pressure applied and temperature, and surface area of contact [41]. Values of body resistance including skin range from 500 Ω to 3000 Ω with the internal resistance of approximately 300 Ω [41]–[43].

If a mean lightning current strike the head of a person the voltage from feet to head could reach up to about 30 MV, considering a mean lightning peak current value of 30 kA, such as that of Table 1-1, and a body impedance of about 1 kΩ. With this high voltage value, most of the time a larger portion of the lightning current flows on the body surface, as a flashover, avoiding the flow inside it. In homogeneous conditions, to produce an air breakdown to spark formation it is required an electric field of 3 MV/m (30 kV/cm), i.e., for a 1.8 m tall person, a voltage of more than 5.4 kV is enough to produce a flashover. On the other hand, if it is considered an internal resistance of the human body of 300 Ω [43], the voltage feet to head caused by a 30 kA lightning could be up to 9 MV, still enough to produce an outside flashover. This effect is likely the responsible of many people have survived after a direct lightning strike [39], [40], [43]–[45] as will be discussed below.

The danger to people mainly depends on the current path, magnitude, and duration of the current flow, even though some injuries are not directly related to the path of the currents. The impedance of a human body's pathway varies with the touch voltage, resulting in a non-linear relationship between current and voltage. Therefore, the data on this relationship is required. The admissible limit of touch voltage (i.e., the product of the current through the path of the body – called touch current – and the body impedance) as a function of time is the basic criterion of the danger. The parts of the human body (such as the tissues, joints, muscles, skin, blood, etc.) present to the electric current a certain impedance composed mainly of resistive and capacitive components [41], [46] but also inductive ones.

2.2 Lightning hazard and risk

Hazard and risk are concepts often confused with each other. According to the online Oxford Dictionary, **hazard** “is something that can be dangerous or cause damage”; **danger** “is the possibility of something happening that will injure, harm or kill somebody, or damage or destroy something”; and **risk** “is the possibility of something bad happening at some time in the future, a situation that could be dangerous or have a bad result” [47]. Figure **2-1** shows an adaptation of a graphical piece from European Food Safety Authority – EFSA about the concepts of hazard and risk with an example for lightning [48]. According to the Authoritative Dictionary of IEEE Standards Terms (IEEE Std 100-2000), hazard is “a threat to the health, survival, or reproduction of an organism from some natural or artificial agent or event” while risk is “a measure of the probability of experiencing harm from one or more hazards (e.g., accidents, toxic chemicals)” [49].

Figure 2-1. Banner of EFSA about the difference between Hazard and Risk, here particularly for lightning. Source: adapted from www.efsa.europa.eu [48].

In the Canadian Centre for Occupational Health and Safety website (www.CCOHS.ca), one can found that "a hazard is any source of potential damage, harm or adverse health effects on something or someone. Basically, a hazard is the potential for harm or an adverse effect (for example, to people as health effects, to organizations as property or equipment losses, or to the environment)", and on the other hand that "risk is the chance or probability that a person will be harmed or experience an adverse health effect if exposed to a hazard. It may also apply to situations with property or equipment loss, or harmful effects on the environment" [50]. A hazard is something that poses an immediate or long-term health effects on the environment or people, while a danger is something that poses an immediate physical or chemical effect. Then, hazard is more general than danger, and risk quantify the probability of the hazard negative effect. The higher the risk, the worst the hazard effect.

As it was shown in the example of Figure 2-1, lightning strikes are a hazard, but when someone is exposed against them in unsafe conditions they become in a risk. John Jensenius, retired specialist on lightning safety of U.S. National Weather Service, stated circa 2006 that: "People are struck because they are in the wrong place at the wrong time. The wrong place is anywhere outside. The wrong time is anytime a thunderstorm is nearby" [51], [52]. The greatest risk for a person, in worst place and at worst time, could be to stay outdoors near a tree or a tall structure in the interval before the approach and after the retreat of a thunderstorm, in a season prone to a high lightning activity, within the time frame of the day with the statistically reported highest lightning activity, and away from medical support.

According to IEC62305-2, **risk** is the "value of probable average annual loss (humans and goods) due to lightning, relative to the total value (humans and goods) of the structure to be protected", and **tolerable risk** is the "maximum value of the risk which can be tolerated for the structure to be protected" [24]. The representative value of annual tolerable risk in the standard for loss of human life or permanent injuries is 10^{-5} a^{-1}, this is the 10 % of the risk value assumed for loss of cultural heritage, and 1 % of the risk value for loss of service to the public and for loss of economic value. IEC62305-2 states that it is "the responsibility of the authority having jurisdiction to identify the value of tolerable risk", then, it is possible to adopt as Non-tolerable the risk of loss of human beings for lightning protection regardless of the economic cost.

Some factors are determinant in assessing the risk of lightning injury as shown in Table 2-1 where the main factors that could be used to determine the risk of being injured by lightning is summarized.

Table 2-1. Determining factors in the risk of being injured by lightnings. Source: adapted from [40].

Exposure
Lightning density, measured as flash rate density FRD but in number of cloud-to-ground flashes/square km/year (CG flashes $km^{-2}a^{-1}$)
Population density
Availability of safe areas to escape from lightning
Existence of lightning safety guidelines
Knowledge of lightning safety guidelines
Compliance with guidelines

2.3 Interaction mechanisms between lightning and victims

Several lightning-caused traumata are recognized by the interactions with their victims as coupling mechanisms, either electrical, nonelectrical, or a combination of both. Electrical currents, heat production and concussive forces are the main ways of injury [26], [53]. Figure 2-2 lists the interactions of the lightnings that can harm living beings grouped according to the main mechanism type. All these mechanisms include the effect of electric current on the body tissues, burns due to dissipation of electrical energy as thermal energy, mechanical trauma through a variety of mechanisms including being thrown due a transmitted shockwave, flying debris (or shrapnel) from an object in the vicinity due to shockwave or the direct strike, fall secondary to being struck or due to muscle contraction reaction [54]. Indirectly, lightning may injure through fires, in forest or in house, falling objects, or explosions [38].

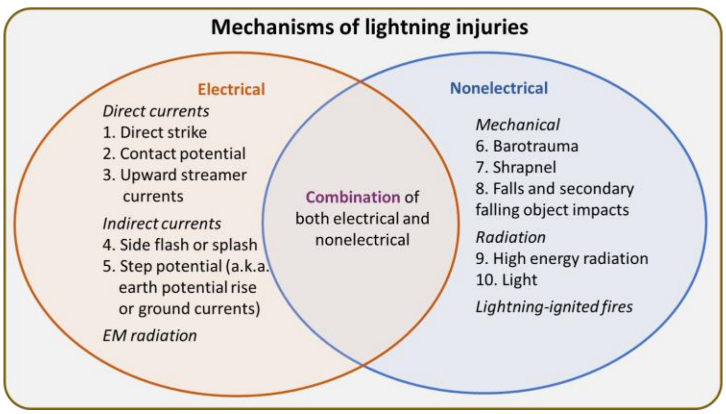


Figure 2-2. Mechanisms of lightning interactions that can injure living beings. Source: author.

2.3.1 Electrical mechanisms of lightning injuries

As electrical phenomenon, lightning has electrical mechanism of interaction with humans and living beings. In technical literature it is possible to find that there are seven or eight coupling mechanisms that have been identified to explain the interactions between lightning and humans [55], [56]. There are five well-identified and recognized electrical-based mechanisms of lightning interactions caused by direct and indirect electrical currents that can produce different pathologies: direct strikes, contact potential, side flash or side splash, step potential (also known as earth potential rise or ground currents), and upward streamer currents [3], [55], [57]. These mechanisms are related to estimated number of fatalities in developed countries, but there are not estimates for developing countries [38], [58]. Most lightning injuries involve at least one of these physical mechanisms and often some combination of them.

a. Direct Strike. It occurs when the lightning flash directly strikes the body. Sometimes the current at the base of the lightning channel cross into the victim body from the strike point [4], [38] but it has shown that frequently it is formed an outside surface flashover. “The surface flashover reduces the damage that would have occurred to the body if all current had flowed internally” [7]. That outer disruptive discharge could have a “protective effect” by avoiding dangerous currents from entering the body [7], [45]. Direct strike most often occurs in outdoors when people does not have a safe location to shelter. The head and shoulders are the main targets of attachment when a lightning strikes directly a human being [58].

Direct strikes are often thought to be the most likely lightning-cause fatalities, but there are no studies on the relative fatality rate for each strike mechanism and the estimated death occurrences is based on the examination of thousands of cases by physicians and specialists. The figure most accepted for the frequency of fatalities by direct strikes corresponds to 3 % to 5 % of all lightning deaths in developed countries [3], [38], [59].

Figure 2-3 depicts a sequence of the electrical situation to understand the interaction of direct lightning with the human body presented in the book of Uman [7]. Lightning it is assumed to start flowing between feet to head from the ground, increasing over time during the upward-connecting leader phase. Here in this phase, the inside currents that enable upward streamers are related as another cause of injury as will see below. During this period of about 1 ms or more, the inside body current and voltage increase from zero to 100 A and from zero to 70 kV (Figure 2-3 a). Subsequently, the first stage of the return stroke from 100 A at the end of previous phase up to 1000 A in takes a time of about 1 μs (Figure 2-3 b). Assuming a critical electric field intensity of about 500 kV/m to breakdown in a gap of the average human heigh, this is 1.8 m, a flashover through the air beside the surface of the human body will be expected if the voltage between head and ground exceeds about 900 kV (i.e., 500 kV/m × 1.8 m). If the person is wet as in a rainy case, the electrical field intensity for breakdown may be lower by up to a factor of about two, lowering the value of the breakdown voltage. Considering the body resistance between 350 Ω to 1400 Ω and taken the middle value of 700 Ω, a flashover at 900 kV corresponds to lightning current across the body of approximately 1.3 kA (i.e., 900 kV/700 Ω) as shown in Figure 2-3 c.

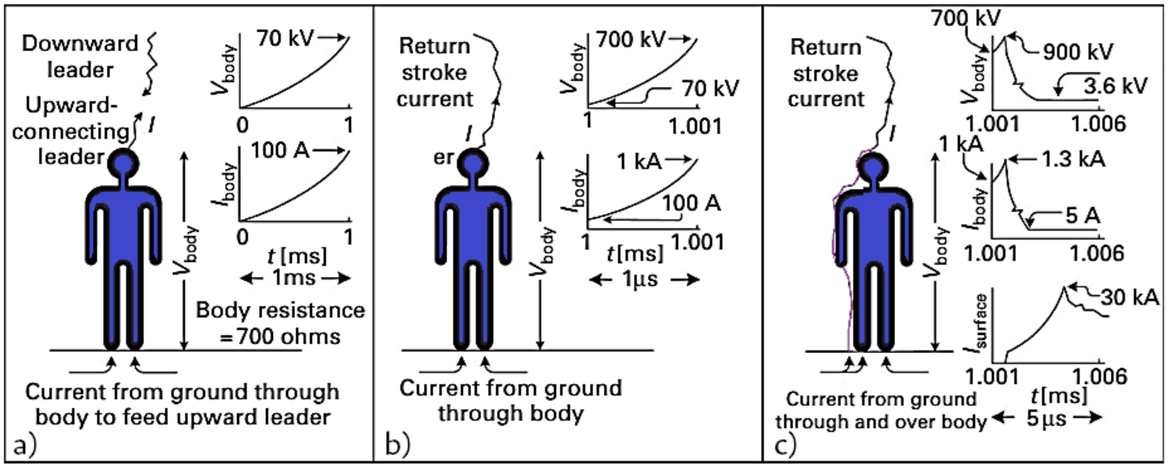


Figure 2-3. Electrical aspects of a lightning strike to a human: (a) upward-connecting leader phase, (b) initial return stroke phase, and (c) surface flashover at I = 1.3 kA and V = 900 kV and thereafter. Source: adapted from Uman [7, p. 126].

In this flashover phase, the body current increases from 1 kA of the previous phase to 1.3 kA, allowing the breakdown besides the body surface, lowering the voltage and the current in the body. The surface flashover besides the body occurs in the return stroke current's rise to peak value, reaching tens of thousands of amperes, in Figure 2-3 c, up to 30 kA. The typical electric field along any arc, here formed through the air outside the body, is about 2 kV/m. Thus, the flashover reduces the voltage head-to-ground from 900 kV to 3.6 kV (i.e., 2 kV/m × 1.8 m), lowering the inside current from a peak of about 1.3 kA to about 5 A (i.e., 3.6 kV/700 Ω) in a time around 1 µs, maintaining this value until the outside flashover disappear. Therefore, it is very likely that the surface flashover has a protective effect against lightning, preventing death as suggested on the works of [7], [45], [60], [61].

b. Contact Potential. Also, it is known as touch potential or contact voltage. It has been estimated that contact injury occurs in about 3 % to 5 % of all lightning-caused fatalities [38], [59]. It occurs when a person or animal makes direct contact onto an object struck by a lightning. Between the ground, as the first contact point of the victim, and the contact or hold point between both the struck object and the victim, as the second point, it is formed a parallel impedance where the current divides, resulting in a voltage gradient. This mechanism is common when a living being touch objects struck by lightnings that are good conductors or not good insulators such as metallic structures, wire fencings, hard wired telephones, plumbing or trees. Another unusual way of contact potential is through wet ropes where lightning currents can go through and should be avoided as could be equivalent in risk to conductive wires [62], [63].

c. Side Flash. Also, it is known as side splash. This mechanism accounts for about 30 % to 35 % of lightning-related fatalities. It occurs when a streamer jumps form a lightning struck object such as a tree, structure, a pole, or building, down to a nearby victim, also occurring from person to person. Then, the main current is diverted between the two paths, like in the contact potential mechanism, in inverse proportion to resistance of each path. The entire lightning current or a part of it may pass through the victim [58]. Standing under or close to trees or other tall objects is dangerous and must be avoided during or near a thunderstorm (approaching, during, and moving away). [3], [38], [58]. In someone standing, for example near a tree, a side flash may hit any part of the body [58]. These electrical coupling mechanisms between human and lightning are depicted in Figure 2-4.

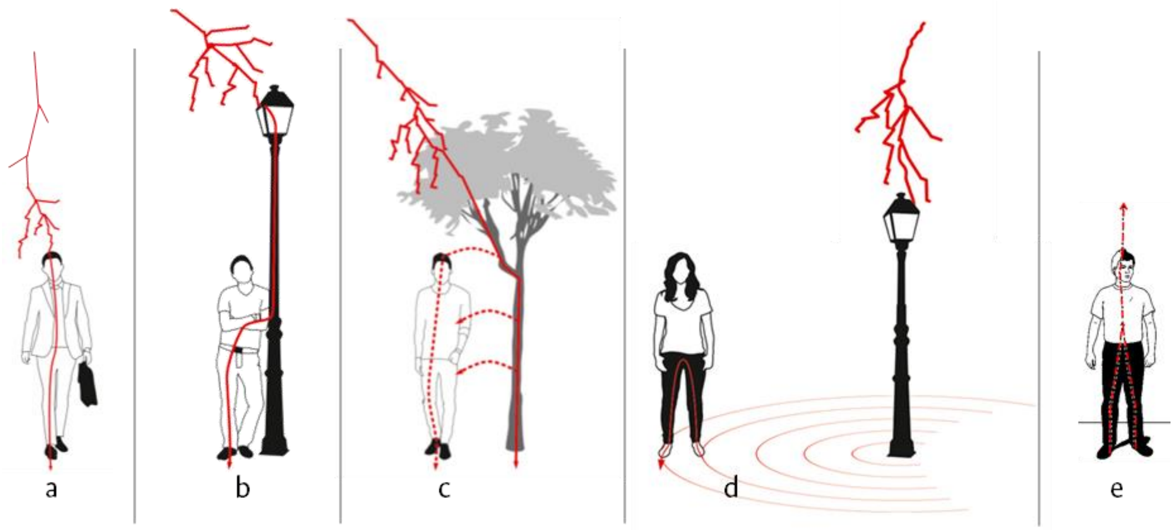


Figure 2-4. Mechanisms of electrical lightning interactions that can injure humans: a) direct strike, b) contact potential, c) side flash, d) earth potential rise, and e) upward streamer. Source: adapted by the author from VDE e.V. [64] and from Cooper et al. [38].

d. Earth Potential Rise (EPR). Also known as step potential, step voltage, or ground current, this mechanism has been estimated to cause death in approximately 50 % to 55 % of all lightning accidents [59]. This occurs because soils are not perfect conductors but consists of layers with finite resistance. However, it is assumed that lightning currents injected into the ground travel through it as they would in a conductive material. If an individual has points of contact with the non-ideal ground in the vicinity of the strike point, a potential difference is set up between the contact points of the victim by the ground resistance and the current flow [3]. It is said then that the voltage of the earth is raised [38].

Assuming the soil as uniform and isotropic, the lightning current would spread out into the ground uniformly around a hemisphere, as represented in Figure 2-5 (a), then the total current passing through any hemisphere layer at a radial distance r will be the total current applied by the lightning in the strike point [4]. Then, the current density $J(t)$ for any hemisphere at any time t at a distance r is given by Eq. 3,

$$J(t) = \frac{I(t)}{2\pi r^2} \qquad \text{Eq. 3}$$

Considering a homogeneous soil with a conductivity σ, the electric field $E(t)$ at any point on hemisphere of radius r is given by Eq. 4 and represented in Figure 2-5 (b),

$$E(t) = \frac{J(t)}{\sigma} = \frac{I(t)}{2\pi r^2 \sigma} \qquad \text{Eq. 4}$$

The potential difference V between two points separated a distance s in the direction of r is given by Eq. 5, and its maximum value given by the peak current as shown by Eq. 6.

$$V = \frac{I(t)}{2\pi\sigma r^2} r - \frac{I(t)}{2\pi\sigma(r+s)^2}(r+s) = \frac{I(t)}{2\pi\sigma}\left(\frac{1}{r} - \frac{1}{r+s}\right) \qquad \text{Eq. 5}$$

$$V_{peak} = \frac{I_{peak}}{2\pi\sigma}\left(\frac{1}{r} - \frac{1}{r+s}\right) \qquad \text{Eq. 6}$$

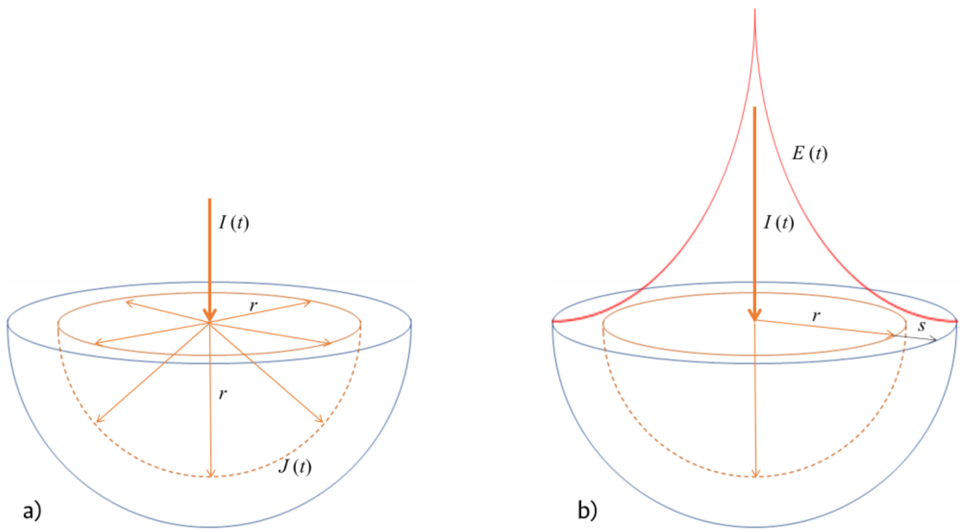


Figure 2-5. Schematic representation out of scale of (a) current density $I(t)$ at a distance r and (b) the electric field $E(t)$ in a uniform and isotropic soil due to an electrical current. Source: author.

According to Eq. 6, these voltages in the ground decrease in magnitude with distance from the strike point [42]. The closer the contact points are to the strike point, the greater the potential rise between those points. As shown in Figure 2-6, the potential on earth between the victim contact points is higher near the location of a cloud-to-ground lightning strike. A voltage of enough level between contact points can cause serious injury if currents flowing inside the body pass through a vital organ. More damage it is expected as the distance increase between these contact points. For example, head to heels in a lying down on the ground, or front and rear legs of four-legged animals have greater potential values than between the feet in a person who is walking. Considering the heart between the front legs in cattle, a moderate lightning strike could produce enough potential difference in the path of the currents to cause an infarction or any other serious injury [65].

In Figure 2-6 is represented out-of-scale the lightning strike point, the electric field funnel inverted, the concentric equipotential lines, and three situations: a person lying down on the ground, a person walking close to the strike point, and a person walking approaching to the strike point but at a safe distance.

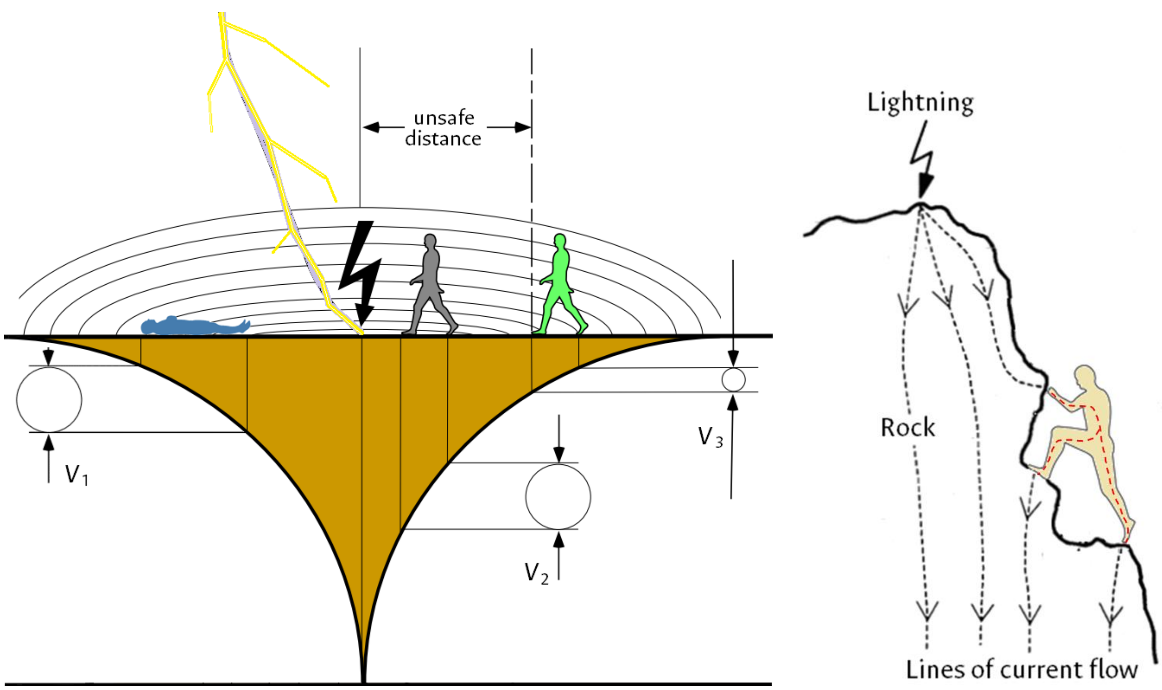


Figure 2-6. The earth potential rise on the ground can produce the circulation of dangerous currents inside the human body. The closer to the strike point, the greater the potential rise. The lightning currents also can flow as surface arc discharges in some conditions as shown for a hill struck by lightning and some paths cross through a climber's body. Source: author, adapted from [25], [66].

Additionally, current flow lines in surface trajectories are depicted for a case in which lightning strikes the top of a hill and the current passes thorough the body of a climber.

Commonly, the high resistivity of the rock and soil composition of upper part of mountains and hills contribute to lightning currents flow as arc discharges along the surface [66].

As shown before, the soil type, the lightning peak current, the distance to the strike point, and the contact points separation are the parameters to estimate the voltage produced. However, despite not being included in the equation, the organism's body condition plays an important role in the consequences of the injury.

Some estimated values of the potential difference between contact points for a 1.8 m tall person with a 0.5 m step are provided in Table 2-2. We considered a typical current peak value of 30 kA (from Table 1-1), an ideal soil with a typical conductivity of uplands of σ = 0.016 S/m [67], [68], and a safe distance as one that produces less than 200 V between the 0.5 m step, that is, 30 m. Soils with lower conductivities lead to higher voltage values. Only by taking a lowlands type soil, with a conductivity greater than upland ones, for example of σ = 0.120 S/m according to [68], a previously unsafe situation becomes safe. On the other hand, this could help to explain why acute injuries are reported at upland places [38], [39], [62], [69] where the soil is drier, resulting in less conductive soils.

Table 2-2. Some estimated values of earth potential rise V_{peak} related to the situation of a 1.8 m tall person regard to a strike point.

situation / parameter	at safe distance to strike point		lying down on the ground		at unsafe distance to strike point	
σ / (S/m)	0.016	0.120	0.016	0.120	0.016	0.120
r / m	30		20		10	
s / m	0.5		1.8		0.5	
I_{peak} / A	30 000		30 000		30 000	
V_{peak} / V	163	22	1232	164	1421	189

However, based on some mathematical circuit simulations for an average person in walking position, it has been found that properties of different soils do not expressively affect the possible harmful current that could reach the heart [70] as the main current flow between feet. To prevent these currents through the body the use of dielectric shoes cannot be considered an effective measure. Experimental simulations show that the dielectric material of a shoe's sole is not an enough protection against lightning currents as the ground potential could overcome the dielectric strength of the sole material, particularly around the seams or joints of the sole with the upper, allowing current flow through the body [71].

An effect of the EPR is the **surface arcing** on the ground, due in part to high currents and ionization processes that lead to discrete breakdowns and filamentary arc [66], [72] over the non-homogeneous ground**.** As soils are commonly non-homogeneous with several layers, upper stratum conducts the lightning currents and can flows as surface arc discharge. In rocky soils the resistivity can be very high, suitable for current flow as surface discharges, and even if the surface is wet, the probability becomes higher [66]. It has been seen lightning arcs flowing over ground surface and some similar effects reproduced in laboratory [72]. EPR can injure multiple victims at a time by the process itself and it is often found in arcs around the cloud-to-ground strike points. Large groups of humans and animals have been injured by EPR, some linked to surface arcing, on remote wilderness settings, baseball fields, at racetracks, in hiking or camping, and during military operations [55], [65], [73], [74].

e. Upward streamers. The last identified form of electrical injury from lightning is through a connecting leader current [4] also known as upward streamers, that can be considered an early phase of a possible direct current as shown above (Figure 2-4). As a stepped leader approaches above the ground, multiple connecting leaders can rise from various grounded objects or from the flat ground in response, toward the stepped leader moving downward. Commonly only one of these upward streamers makes the connection with the stepped leader and the ground. Figure 2-7 shows an image section of a photograph taken in southern New Mexico, USA of a –14.8 kA lightning attachment obtained with a total exposure time of about 10 s [75].

Figure 2-7. Image magnification of a lightning attachment photograph taken in southern New Mexico, USA, showing at least 12 unconnected upward leaders in the form of branches emanating from the ground. Source: [75].

This image displays approximately 12 positive unconnected upward leaders in the form of white branches around the attachment to the ground. Although the current amplitudes in upward streamers are not precisely known, it is estimated that in well-developed positive leaders these currents range from ten to hundreds of amperes, more than enough to cause injury. Even when a ground termination is more than 200 m away, each upward streamer could reach more than 100 A [75].

There is a classic photo, shown in Figure 2-8, used commonly to warn people about lightning risk. The photo captures two brothers with their hair standing on end just moments before being struck by lightning. It was taken on August 20, 1975, as they were descending from the top of Moro Rock, at an elevation of about 2000 m.a.s.l. in Sequoia National Park, California, USA [76]. The younger one suffered full thickness burns in her back and elbows and his brother was unharmed. Another man who was near the place lost his life by the same lightning event.

As shown in Figure 2-7, upward streamers do not always connect with downward leaders to form the lightning channel. However, they can injure people despite its relatively low current, but may be high enough to impair some bodily functions [23]. An incident with some similarities to that of the brothers, involving a lightning strike that injured a five-man crew leaving one dead was investigated by Cooper in 2002 [77], in which a weak upward streamer could explain the reported events.

Figure 2-8. Two brothers minutes before they were struck by lightning on Aug. 20, 1975. Both brothers survived but the younger one with third-degree burns. Source: [78].

Figure 2-9 shows the published lightning fatality rates per year for several countries [79] and a chart of estimated primary lightning fatalities in a developed country where the use of lightning protections system is a common practice in buildings and structures [38]. It is clear that the figures do not benefit the least developed countries, although the statistics should be taken with care.

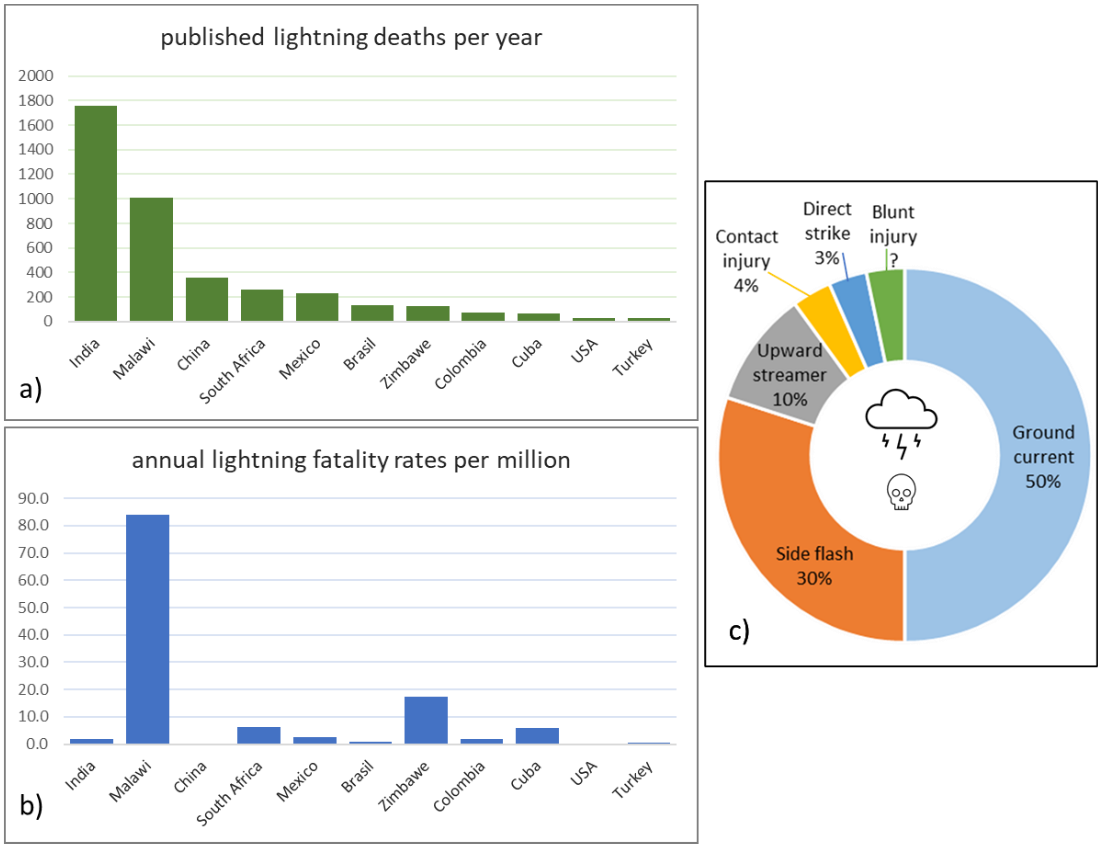


Figure 2-9. Published annual lightning fatality deaths for top 11 countries (a), fatality rates per million people (b), and primary lightning fatalities in a developed country (c). Source: (a) and (b) adapted from data of [79] and (c) from [38].

2.3.2 Non-electrical mechanisms of lightning injuries

Most lightning-caused injuries and deaths are not due to direct strikes currents but to the indirect effects of flashes that strike other and more prominent targets, and to the secondary effect of lightning-induced fire [4], [40], [57]. Mechanical, lightning-ignited fires, and radiation effects of lightning can be considered as non-electrical mechanisms of lightning injury as shown previously in Figure 2-2.

Barotrauma. The channel temperature of a lightning strike can raise above 25000 K in a few microseconds, increasing the pressure around the lightning channel to several atmospheres (1 atm = 101.325 kPa) resulting in shock waves by the expansion of the air.

The rapid outward movement of air like an explosion, can be enough to knock a close living being down in the proximities, or cause impact injury to their internal organs.

The explosive overpressure creates a force that can hit a person or any close object after the lightning strike, causing injury as would a fall or other concussive shock, affecting or damaging internal organs or leaving musculoskeletal injuries. Also, this mechanism can cause a person to be thrown away or the secondary fall of objects that can indirectly cause traumatic injuries.

Shrapnel. In this case, it is produced an explosion possibly produced from enclosed moisture in materials that expands rapidly by lightning impulsive currents that can cause heating resulting in a vapor explosion, then, material as flying debris or shrapnel is blowing away outward from the bulk mass. For example, lightning strike can blast shrapnel from a tree bark, or blunt material from bricks or masonry, producing penetrating trauma into a person in the path of the ejected material. Penetrating injuries due to lightning strike blast are extremely uncommon. However, these "shrapnel" injuries cannot be discarded when people are exposed to nearby lightning strikes [80].

Light and high energy radiation. The lightning channel is a very strong source of visible and ultraviolet radiation, and has recently been shown to give rise to X-ray and gamma radiation that appears to play a role in the leader propagation [81]. The strong radiation from the lightning channel can cause medical problems to the eyes, with cataracts being the most common long-term injury related to lightning.

Lightning-ignited fires. The secondaries fires produced by lightning strikes cause damages and losses to people, property, and nature. For the period from 2007 to 2011, the U.S. National Fire Protection Association (NFPA) reported an average of 9 people deaths, 53 injured, losses of $ 451 million in direct property damage per year in USA [82]. Lightning-ignited fires accounts for approximately half of all wildlands fires in Western North America [83], [84]. Lightning fires are most prone in the summer months, during the heat waves, in the late afternoon or early evening [82]. In the Amazon forests, lightning fires are less likely even when lightning strikes trees, as the humidity is so high and the treetops so thick that the flames usually die out on their own [85].

In buildings and human structures, type and materials have an important effect against lightning fires, as expected. Older and unprotected farm barns commonly have not conductive paths to ground, resulting in instantaneous ignition of current paths when lightning currents travels through the roofing, siding, and framing flammable materials [57]. In developing countries, particularly in non-urban areas, most buildings are made with materials such as mud and straw, masonry, cardboards, and wooden materials for the walls, with thatch roofs or tile sheet metal roofs, many times without an appropriate fastening. Such structures with easily flammable materials can catch fire when lightning currents pass through them [26], [40], [86]. On the other hand, isolated and ungrounded metallic roofs (such as sentry boxes, shacks, or gazebos) are not safe against lightning discharges [69] which can act as floating electrodes that could also induce fires inside the shelters.

2.3.3 Lightning-caused injuries

An injury can be defined as a bodily lesion at the organic level, resulting from acute exposure to energy (mechanical, electrical, thermal, chemical or radiation) in amounts that exceed the physiological tolerance threshold [87].

There are several lightning-related pathologies, as reported in media, technical, and medical literature regarding a wide range of injuries directly or indirectly linked to lightning phenomenon. The field of study of the effects of lightning on health is known as keraunomedicine (root from Greek word keraunos – *κεραυνός* – meaning lightning). Cooper and Holle [40] present a compendium of information on lightning injuries from more than 35 years of medical observations and analyses, and many reports from own and other several sources, codified by signs and symptoms. Kitagawa, Andrews, Cooray, Uman, Jensen, and others [3], [6], [7], [23], [60] have also present valuable information about lightning effects on humans and living beings.

The most common and intuitive lightning-caused injuries on humans are death, superficial burns, and rupture of the eardrum. However, there are many different types of injury to heart, ear, eye, nervous system, paralysis, psychological, impact or blunt trauma, penetrating injuries, and others that may result in short-, medium-, or long-term disability. In Table 2-3 are synthetized some of the most common injures that lightning can cause to humans and that could also harm animals, related to lightning coupling mechanism.

Table 2-3. Some lightning-caused injures, and sign and symptoms manifestation in humans related to the coupling mechanism between lightning and human. Data from: [6], [40], [54].

Organ or system	Signs, symptoms, injury	Lightning coupling mechanism: Direct strike	Contact potential	Upward streamers	Side flash	Earth potential rise	Barotrauma	Shrapnel	Falls	High energy radiation	Light	Lightning ignited fires	EM radiation
Skin	burns and thermal injuries, shrapnel wounds, scars, Lichtenberg figures	✓			✓	✓	✓	✓				✓	
Heart	cardiac arrest and injures, ECG abnormalities, arrythmias. hypertension, myocardial ischemia, other cardiovascular injuries	✓	✓	✓	✓							✓	
Lungs	pulmonary injures, chest pain, edema, hemorrhage, concussive and respiratory injuries,	✓	✓		✓		✓	✓				✓	
Brain	brain injury, confusion, loss of consciousness, hallucinations, electrical activity disfunction	✓	✓	✓	✓		✓	✓				✓	✓
Neurologic	brain injury, seizures, confusion, amnesia, weakness, dizziness, vertigo, balance problems, phosphenes	✓	✓	✓	✓		✓	✓		✓		✓	✓
Spinal cord	Keraunoparalysis, spinal artery spasm, hemi- or quadriplegia	✓	✓		✓				✓			✓	✓
Neuro-psychologic	memory difficulties, forgetfulness, attention deficit, distractibility, depression, loss of executive function, irritability, mood disorders, personality changes, anxiety, sleep disturbances	✓	✓	✓	✓	✓	✓	✓				✓	
Musculo-skeletal	muscle aches, involuntary contractions, chronic pain syndromes, atrophy, concussive	✓	✓		✓	✓	✓	✓	✓			✓	
Ear	tinnitus, eardrum rupture, hearing loss, vertigo, hyperacusis	✓	✓		✓		✓	✓	✓			✓	
Eye	changes in vision, phosphenes, cataracts, macular holes, retinal shifting or detachment, wrinkles, photophobia, burns	✓	✓	✓	✓		✓	✓		✓	✓	✓	
Endocrine	endocrine dysfunction, menstrual irregularities, decreased libido	✓	✓	✓	✓	✓						✓	

Skin lesions resulting from lightning currents can be thermal lesions such as linear, punctate, or other thermal injury, and keraunographic markings over the skin such as feathering lesions or Lichtenberg figures, also known as ferning patterns. Figure 2-10 shows some images related to lightning skin injuries. Lichtenberg figures (Figure 2-10 number 5) are not usually present in people struck by lightning, may remain for several hours and disappear without specific treatment without no known residual effects [88].

Burns are very often associated with lightning strikes and can be since superficial to full thickness, with superficial burns commonly observed. Linear burns as partial thickness occur by vaporization of sweat consequence of lightning-currents flow over the wet skin (Figure 2-10, 2), as was reported in the case of a soldier injured by a lightning strike in a semi-undergrounded shelter [39], [69]. Clustered circular burns and punctate burns (Figure 2-10, 4) are due to current flow to and from deep tissue to exits the body, and in the input and output lightning current points. Full thickness burns are infrequent, estimated to occur in less than 5 % of all lightning injuries, but can occur when metal objects or synthetic fabrics are overheated and melts, burning the skin [38], [39], [54], [69], [88] (Figure 2-10, 1 and 3).

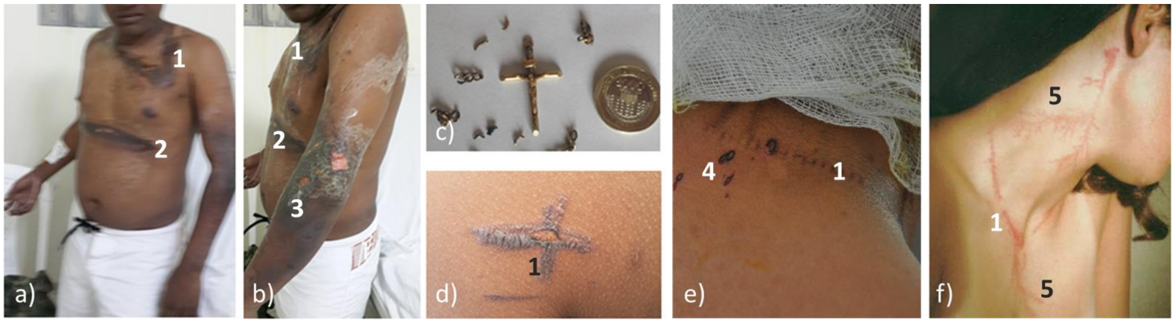


Figure 2-10. Skin lesion by lightning currents. The numbers represent the skin lesion type: 1- thermal by overheated metal in contact, 2- linear burns, 3- superficial to full thickness, 4- punctate, 5- ferning patterns. Source: a) to e) adapted from [39], [69], and f) adapted from [89].

Blunt injury by barotrauma is not uncommon and can occur either caused by a person being thrown due to massive instantaneous contraction of extremities from by the crossing current or by the explosive force resulting from the powerful shock wave consequence of the suddenly superheat of the air surrounding the lightning channel and their posterior rapid cooling [54]. The shock wave can cause concussive injury such as eardrum rupture, organs contusions, and abnormal accumulation of air between the lungs and the chest wall which is known as pneumothorax. In addition, it can lead to multiple forms of trauma from secondary falls or strikes with other objects, with the possibility of many other injuries such as bone fractures, cervical spine injury and internal bleeding [40], [54].

Ocular and auditive injuries can occur if the current passes through the head or the strong radiation produced by the lightning channel is enough to produce damage. Also, blunt or blast trauma, vasoconstriction, or heat damage are common sources of eye and ear damage. Cataracts are the most common ocular injury. Injury to the audio-vestibular system could be produced by either barotrauma or electrical mechanisms.

Tympanic or eardrum membrane rupture is common, founded in 50 % to 80 % of people struck by lightning. Hearing loss is common but temporary, as also tinnitus, vertigo, or facial nerve paralysis [6], [40], [54].

Cardiac arrest can lead to death after a lightning strike due to cardiac and respiratory arrest, common in direct strikes. Usually, victims can have an asystolic arrest due to an immediate and simultaneous depolarization of all myocardial cells, with posterior returning of sinus rhythm and spontaneous circulation. A second cardiac arrest may occur because of continued paralysis of the medullary respiratory center when proper and opportune treatment is not given to the victim. Commonly, at the time of the injury, the cardiac arrest is the only cause of death. However, in developing countries, indoor lightning-ignited fires could be the most common cause of death [40], [54].

Keraunoparalysis which is a transient paralysis of muscular structures in the line of the current whose cause remains unclear, belongs to pathophysiological effects defined as “stimulatory or inhibitory effects which lead to reversible or irreversible dysfunction of the affected structures of the organism” according to IEC 60479-4 [90]. It is associated as a neurologic problem these pathophysiological effects that can be of long duration due to stimuli beyond common physiological levels.

This temporary paralysis is more common in the lower limbs, and is linked to vascular spasm and instability of the sympathetic nervous system that arise from near the middle of the spinal cord [54]. Keraunoparalysis of the lower limbs associated to fires can be an explanation of many lightning-caused deaths on houses and buildings conformed or containing easy flammable materials common in developing countries [26], [40], [86].

According to Andrews [6], [23], some nonelectrical injuries, also known as remote injuries, could be have origin in chemical disturbances and also could be a common feature of electrical injury. Since most of these symptoms are not associated with the current path, the cause of these symptoms is not well known.

2.3.4 Multiple Casualties

Often, a single lightning event can cause multiple casualties in humans and animals and can even result in death. Multiple fatal and non-fatal casualties caused by lightning can often be attributed to side flashes or earth potential rise, and even upward streamers. However, reliable reports of such incidents are infrequent [26], [40], [44], [66], [73], [77]. Large groups of humans or animals are at risk of lightning injuries in remote wilderness settings, sports fields, racetracks, hiking or camping, and during military operations. These incidents can be attributed to various mechanisms, some of which are also associated with surface arcing [53], [62], [70], [71]. Injuries in multiple casualties cover a wide range of traumata, from stunning and minor lacerations, passing by burning marks, and even death of several individuals.

Commonly in developed countries, most lightning injuries occur in one or two people at a time, while in developing countries there are several reports of entire families, school classes, and several people of communities being injured or even killed by a single lightning event. Many times, in developing countries, most places where people gather for church, rituals, work, and other activities do not provide lightning protection [26], [40].

Certain human activities in their call of duty are obliged to exposed themselves to the risk of lightning causing multiple casualties. For the years from 2003 to 2013, the Colombian Army reported internally several incidents with multiple injured soldiers, some of which with several direct fatalities caused by the same lightning strike: 8 events with two fatalities, 3 events with 3, and 1 event with 4 dead soldiers, all of these between 14:45 h to 2:45 h [91]. This time have the highest lightning activity registered for the rainiest months in Colombia, between March to November and with the consequent problems for the transportation of victims to the appropriate medical care centers.

In the framework of this research, a paper about multiple casualties by a lightning event in Colombia entitled as “Lightning Incident with Multiple Natives Injured in the Sierra Nevada de Santa Marta, Colombia – Description of Scenario” was presented at the 2019 International Symposium on Lightning Protection (XV SIPDA) in Sao Paulo, Brazil [26]. In this paper was reported the tragedy caused by a single lightning event in which 11 native people were killed and another 15 seriously injured. The showed scenario suggests that the most probable lightning interaction mechanisms were the ground currents (aka earth potential) associated to subsequent keraunoparalysis, and a lightning-ignited fire started on the thatch-roof of the traditional ceremonial house where the indigenous people were gathered. Barotrauma and shrapnel also contributed to the injuries reported. This case with severe injuries caused by lightning fits in the explanation of this traumata in developing countries according to [86], where the combination of keraunoparalysis and flammability of housing construction materials highlights the differences with lightning injuries reported for developed countries.

Moreover, a rare case of a woman in pregnancy and her partner struck by a lightning event was analyzed and presented at ICLP - SIPDA 2021 (35^{th} ICLP & XVI SIPDA) [51]. In this paper, the deleterious effect of the lightning ground currents on the fetus head by the fetal position inside the womb during the third trimester of pregnancy is proposed. Commonly, at the beginning of the third trimester of pregnancy, the fetus turns its body head downward, exposing the forming brain to dangerous currents that could flow between its mother's feet by the earth potential rise produced by a lightning strike.

On the other hand, in 2017 also were presented two papers in XIV SIPDA at Natal, Brazil, one with the analysis of a case in which a single lightning strike caused the death of an entire herd of 83 cattle [65], and the other one with a statistical study related to lightning fatalities on the cattle industry of the Colombian eastern planes region. The most probable lightning mechanisms associated to the cattle deaths were the side flash and the ground currents [65].

The uninjured or less injured victims play a primary role in the attention and rescue of lightning victims. In stormy weather or imminent lightning activity, braking up large groups into smaller ones and spreading them out decreases the number of potential victims. While this strategy may increase the risk of someone being struck, it also enhances the opportunity to provide assistance to those who might be affected [73].

2.3.5 Disability Caused by Lightning

The disability resulting from a lightning-caused injury is a serious problem that can become permanent [40]. The main cause of the disabilities is nervous system injuries linked sometimes to psychological disorders. Most of the injuries are associated with lightning currents that cross the tissues, but there are others not directly related to the crossing of currents such as secondary reactions manifested in emotional, behavioral, and personality changes probably due to biochemical imbalances [6]. Personality changes can often lead to neuropsychological disabilities, which can strain or even break the survivor's closest relationships [40].

Many survivors of lightning strikes cannot or are unable to return to their previous activities, with the significant consequences for both the individuals concerned and their families [4], [6]. Permanent disability in any form can affect up to 74% of lightning survivors [54].

It was shown in our paper entitled "Revisiting a case of lightning-caused trauma in a pregnant woman" presented at ICLP-SIPDA 2021, that a single lightning event left temporary disability in a man and a woman in pregnancy, but a permanent disability in the baby born after the incident due to brain development damage [51], resulting in significant consequences in their social relationships, lives, and family.

2.4 Models of human body

There is currently a lack of technical literature available about paths and magnitudes of electric current through the human body [92] and particularly for lightning currents. There are no International Standards dealing with models of human bodies directly or indirectly affected by lightning currents, nor unified reference values that can be used as those existing for main currents at 50 or 60 Hz [93]. Table 1-6 shows the international standards related to lightning, where the entirely informative Technical Report IEC TR 60479-4:2020 "Effects of current on human beings and livestock - Part 4: Effects of lightning strokes" focuses on showing differences in the effects on human beings and livestock due to lightning strokes versus those effects of electric shocks derived from electrical systems; also includes some worldwide lightning occurrences and climatic effects information, direct or indirect related effects to lightning injuries to the human body, and some safety procedures. The Colombian standard NTC4120:1997 adopted the former IEC 479-1:1994 (with later updates up to the current IEC60479-1:2020), that shows a human body model based in internal impedances, illustrated in Figure 2-11. This simplification is used to represent some basic current paths for contact cases in industrial environments, including some information for direct currents and for alternating currents at larger frequencies than the commercial one.

2.4.1 Electric impedance models

The electric model used by Andrews [94] for the human body, used in several research works [70], [95], [96] is based on a set of resistive and capacitive impedances intended for lightning interaction modelling, as shown in the example of Figure 2-12 with the Roman et al. model that includes a shoe's impedance model. Misbah et al. model includes an additional inductance placed in the torso [96] as shown in Figure 2-13 Other models proposed for low power and electrostatic discharge applications use another point of view. Amoruso and Lattarulo (2007) [97] developed a model based in multiple ovals to represent the human body when exposed to very low frequency electric fields. They also consider the superposition of effects on different parts of the modeled body. This model of lumped parameters for each body part considers not just the resistive and capacitive effects but also the inductive effects. In this way, it is possible to carry out more accurate electric current transient analysis that could be used for lightning currents in the human body.

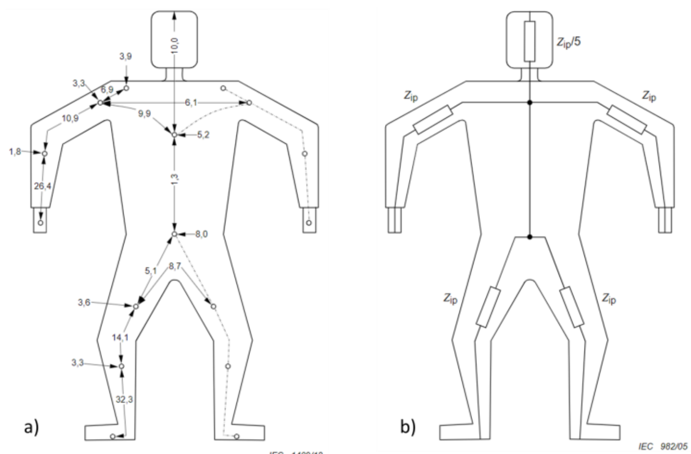
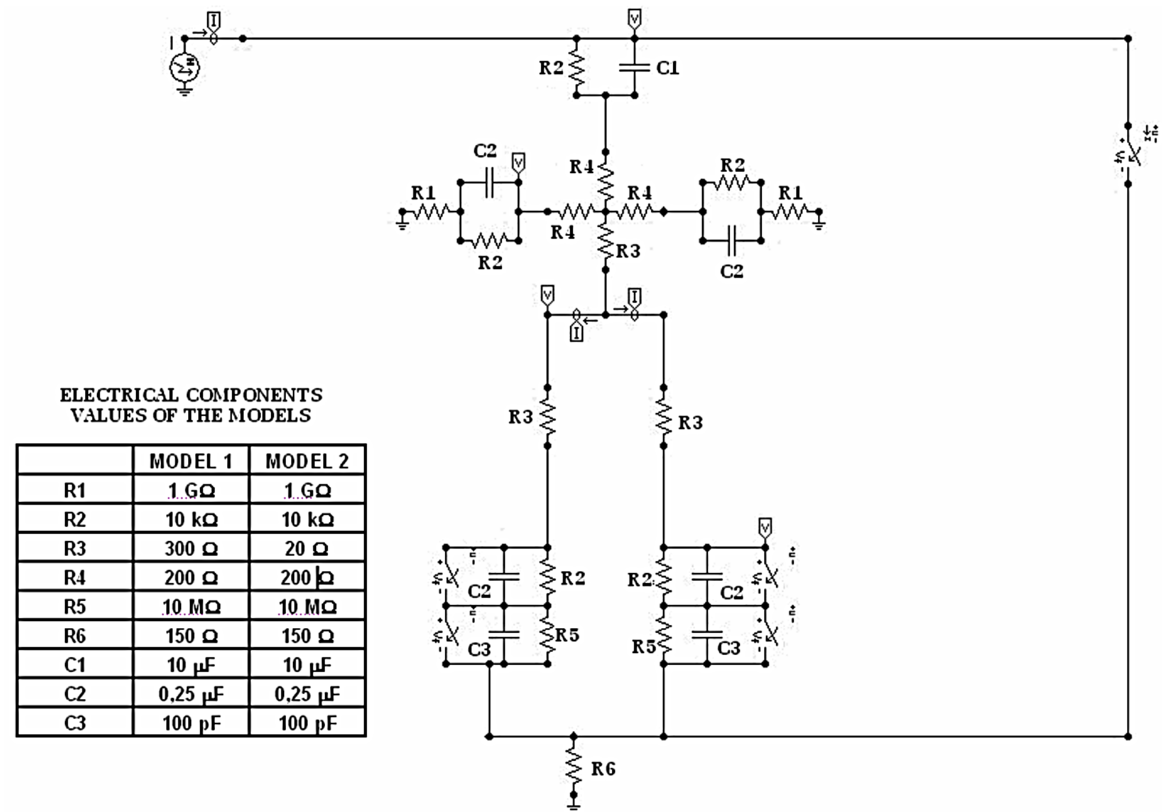


Figure 2-11. Impedance model of the human body showing the internal partial impedances in relation to the hand-foot path (a) and simplified diagram of the internal impedances (b). In (a), the value coming from outside, as skin impedance, must be added to internal impedance for currents entering at that point. In (b) Z_{ip} is the internal partial impedance of an upper or lower limb. Source: adapted from IEC 60479-1 [41].

The Sachse et al (2000) anatomic human body model [98] is based in the processing, segmentation and classification of digital images, leading to a 3D model of the electrical conductivity of the human body. This human body model, which uses the finite difference method for numerical calculation of applied problems such as heart electrophysiology, could also be extended to more broad studies, including lightning accidents.



	MODEL 1	MODEL 2
R1	1 GΩ	1 GΩ
R2	10 kΩ	10 kΩ
R3	300 Ω	20 Ω
R4	200 Ω	200 Ω
R5	10 MΩ	10 MΩ
R6	150 Ω	150 Ω
C1	10 µF	10 µF
C2	0,25 µF	0,25 µF
C3	100 pF	100 pF

Figure 2-12. Roman et al. electrical human body model based on Andrews work [94] including a shoe model, used for mathematical simulations. Source: [95].

It has been shown, in animal experimentation, that body tissues could influence the pathway of currents of less than 1 mA, but larger currents act as if the body behaves like an structureless gel, with no preferred paths for the current, flowing along the shortest path from contact to contact [44]. However, the human body is composed of several fluids and tissues, each with different frequency-dependent electrical properties and the situations in which impedance and lumped models provide valid results is small, since the electromagnetic properties of the human body are nonlinear, dynamic as time-varying, temperature dependent, distributed, and inhomogeneous [99]. Given the complexity of the human body and their tissues, more accurate models are required.

The area of study of the dielectric properties of human and animal tissues belongs to applied and basic science whose results are used in electromagnetic dosimetry (EM dosimetry). This area of study also comprise the simulation of EM exposure and the calculation of the internal fields that appear in the exposed tissues and structures [100]. Therefore, the simplified electrical human body models based on impedances cannot give information about how current is distributed within the body and its organs, tissues, and fluids. On the other hand, practical measurements are difficult to realize and restricted to animal and phantom experiments [97].

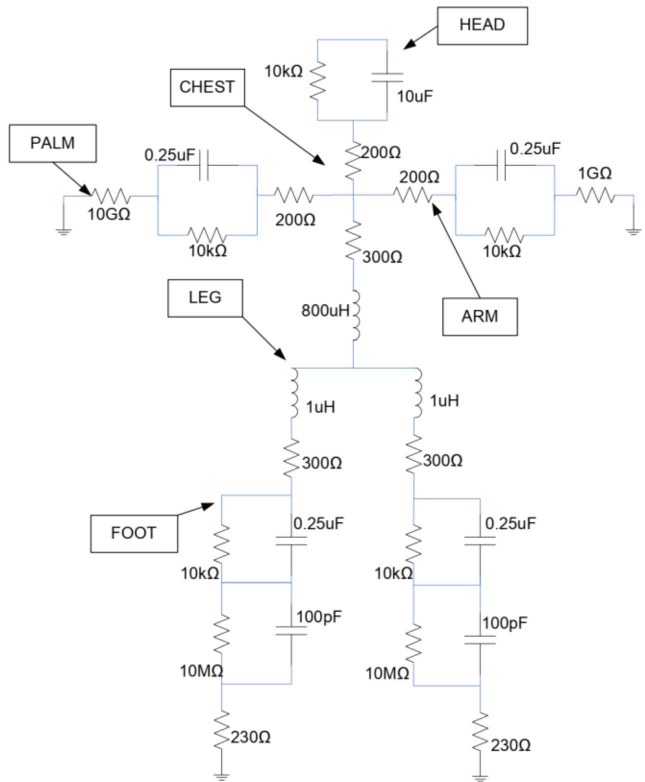


Figure 2-13. Misbah et al. electrical human body model that adds inductances in the torso of the model and the shoe's impedance. Source: [96].

The effects of DC voltages and AC mains voltages on the human body have been researched, documented, and considered in relevant standards. This is not the case for impulsive voltages and currents signals such as those from lightning strike [101].

Despite evolution of human models towards computer-based models, traditional human models based on resistances or impedances are still of interest today when evaluating risk of electrocution and for Electrocardiogram (ECG) potentials analyses [102].

2.4.2 Computer based models

Models of the human and animal bodies, such as physical, mathematical, and computational based, have been used extensively to provide representations of the body in many situations for research in a wide range of fields. However, the complexity of the human body, its tissues and possible pose configurations that occur in nature cannot be reproduced by mathematical models nor by physical phantoms in practice. The so-called anthropomorphic phantoms are used for physical measurements, dosimetry of ionizing radiation, car crash-tests, robotics, and medicine [103].

Models based on computer modeling are mathematical representations of human and animal anatomy to be used in biometric and biomechanics research, and nowadays, also in studies on the effects of electromagnetic fields. Computational human models are used in a wide range of fields such as dosimetry calculations for medicine applications, radiation protection, to study the effects of low frequency electromagnetic fields on human health, and physical measurements [104]. Until recently, the use of anatomically and electrically refined heterogeneous human models was viewed with caution but, results from different institutions using *in-silico* phantom models have become more congruent. It is very likely that standardization based on the results of these more accurate human model calculations will be adopted in the near future [105], [106].

Electromagnetic computer models of the human body can help to understand the mechanisms and effects of lightning strikes and allow to gain insight into the distribution of critical currents inside the body by considering the electrical properties of various organs and tissues. Several computer models have the option of configuring various poses, which was digitized from an originally rigid position.

The Visible Human Project (VHP) addressed by the U.S. National Library of Medicine (NLM) created a complete image dataset of cross-sections of the human body. The project was first planned in 1986, began in 1991 and was completed in its first stage with a male model in 1994 and a female model in 1995. Each model used a cryopreserved cadaver that was cut transversely into thin slices, of 1mm for the male and 0.33 mm for the female. Each sliced image of the entire body was acquired and digitized through computed tomography (CT) and magnetic resonance imaging (MRI) [107]. Each two-dimensional pixel data from such images can be extended into the third dimension, becoming cuboid volume elements called voxels (volume pixels). Voxels can be used to create three-dimensional representation of the shape and composition of the entire body and the internal human organs [108] as shown in Figure 2-14. The smaller the voxel size the better and more accurate the representation of the organs and tissues. The computational human models are also called voxel models or voxel phantoms.

The dielectric properties of several human and animal tissues, both *in vivo* and *in vitro*, were measured at typical body temperature, in the frequency range of 10 Hz to 20 GHz by Gabriel et al., developing a parametric model of the variation of the dielectric properties of biological tissues as a function of frequency [100], [109], [110]. That dielectric properties of each tissue can be assigned to corresponding voxels in the computational human model.

The complex relative permittivity of any material or tissue can be used to obtain the dielectric properties of any material or tissue according to:

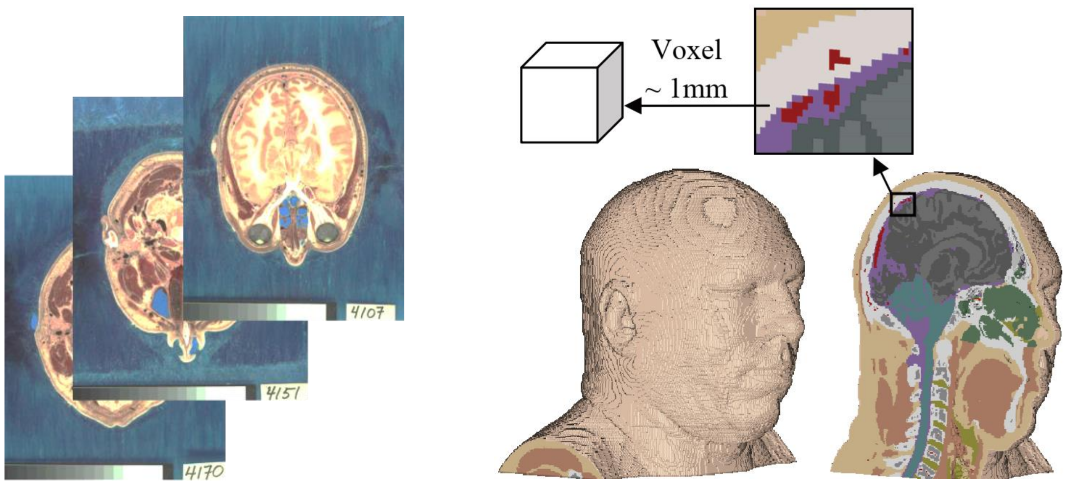


Figure 2-14. From transverse scanned images of the Visible Human Project, 2D pixels are extended to 3D representation becoming voxels. Source: adapted from visiblehumanproject.com and [108].

$$\varepsilon(\omega) = \varepsilon'^{(\omega)} - j\varepsilon''^{(\omega)} = \varepsilon_r(\omega) - j\frac{\sigma(\omega)}{\varepsilon_0\omega} \qquad \text{Eq. 7}$$

where ε_r is the relative permittivity of the material or tissue, dependent on frequency,

σ is the total conductivity of the material,

ε_0 is the permittivity of the vacuum,

ω is the applied frequency.

Dielectric properties are determined by the relative permittivity and total conductivity of the material, which are frequency dependent for biological tissues. Dielectric properties of most human tissues in the range of 10 Hz to 100 GHz were estimated in the Gabriel et al. work [100], [109], [110]. These dielectric properties can also be consulted in the website of the Foundation for Research on Information Technologies in Society (IT'IS) [46] giving the frequency range. The tissue database can also be visualized as a frequency chart, as shown in Figure 2-15. The U.S. Federal Communications Commission (FCC) also has a tool on its website to calculate dielectric parameters of body tissues for frequencies between 10 MHz to 6 GHz (www.fcc.gov/general/body-tissue-dielectric-parameters).

The electrical parameters, such as the permittivity and the electrical conductivity, function of the applied frequency of the tissues under consideration commonly are taken from the outcomes of the research of Gabriel et al. [100], [109], [110]. In that work, the dielectric spectrum of a biological tissue extending from 10 Hz to 100 GHz was modeled as the summation of four dispersion regions. Figure 2-15 shows two screenshots of the Tissue frequency charts for bile and muscle up to 100 MHz, illustrating the electrical parameter differences between the two tissues.

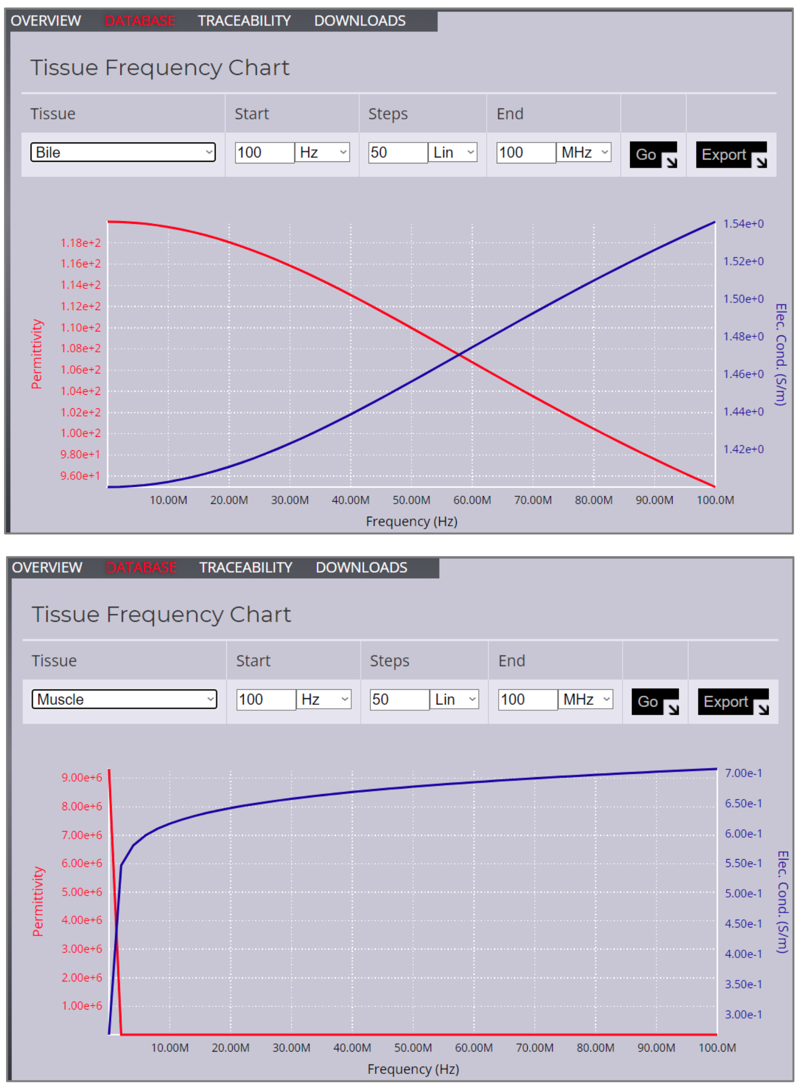


Figure 2-15. Tissue frequency charts for bile (up) and muscle (down) up to 100 MHz. Source: from https://itis.swiss/virtual-population/tissue-properties/database [46].

Several of computer-based body models consist of files optimized for modeling in third-party commercial platforms, such as ABAQUS, ANSYS, CST, or MATLAB, using the Finite Element Analyses (FEA) method. Some of these models are listed in Table 2-4. The results of the electromagnetic modeling simulation commonly are expressed for electric potential (volt), power density (watt per volume), or current density (ampere per area) in the body.

Table 2-4. Some voxel computational based models of the human body for electromagnetic simulations.

Model name	Note	References
HUGO Human Body Model	From Dataset of National Library of Medicine. 32 tissues. Resolution up to 1 mm³, includes poser software.	[101], [107], [108]
CST Voxel Family	From Dassault Systèmes. Seven models (a baby, a child, an adult men, and four women). Up to 135 tissues and organs. Resolution > 1 mm³.	[111], [112]
Virtual Population (ViP) and Vizoo	From IT'IS Foundation (Zurich). Family of 18 human models. More than 300 tissues and organs per model and a resolution of 0.5 mm³. Compatible with a Poser tool.	[113], [114]
Austinman and Austinwoman	From The University of Texas at Austin. Resolution up to 1 mm³. Free available to the public under some conditions at https://sites.utexas.edu/	[115]
Zubal phantom	From Yale University School of Medicine. Adult male human torso (head, neck, and trunk) originally obtained from x-ray computer tomography data segmented into about 50 different tissue types, and resolution about 1 mm³.	[116], [117]

Gao's 2012 doctoral dissertation shows the development of the HUGO Body Model, a voxel-based human body model intended for electromagnetic applications with posable or adaptable postured capabilities [108]. The Gao's work shows that the entire human body model can be simplified as a single wire with different electric potentials at two ends. In this wire model as expected, the equivalent current through any cross section has the same value, with the posture of the human body having almost not influence on the electrical resistance, therefore in the current value of the equivalent circuit [108]. This means that the models of the human body as a whole, despite the different postures that it may adopt, have almost the same electrical resistance, in that work around 3.5 kΩ. This result is approximately in line with standards IEC 60479-1, IEEE Std 80, and IEC 62713 [41]–[43], as it was shown previously in section 2.1. The model and some results of current density of Gao's work are shown in Figure 2-16.

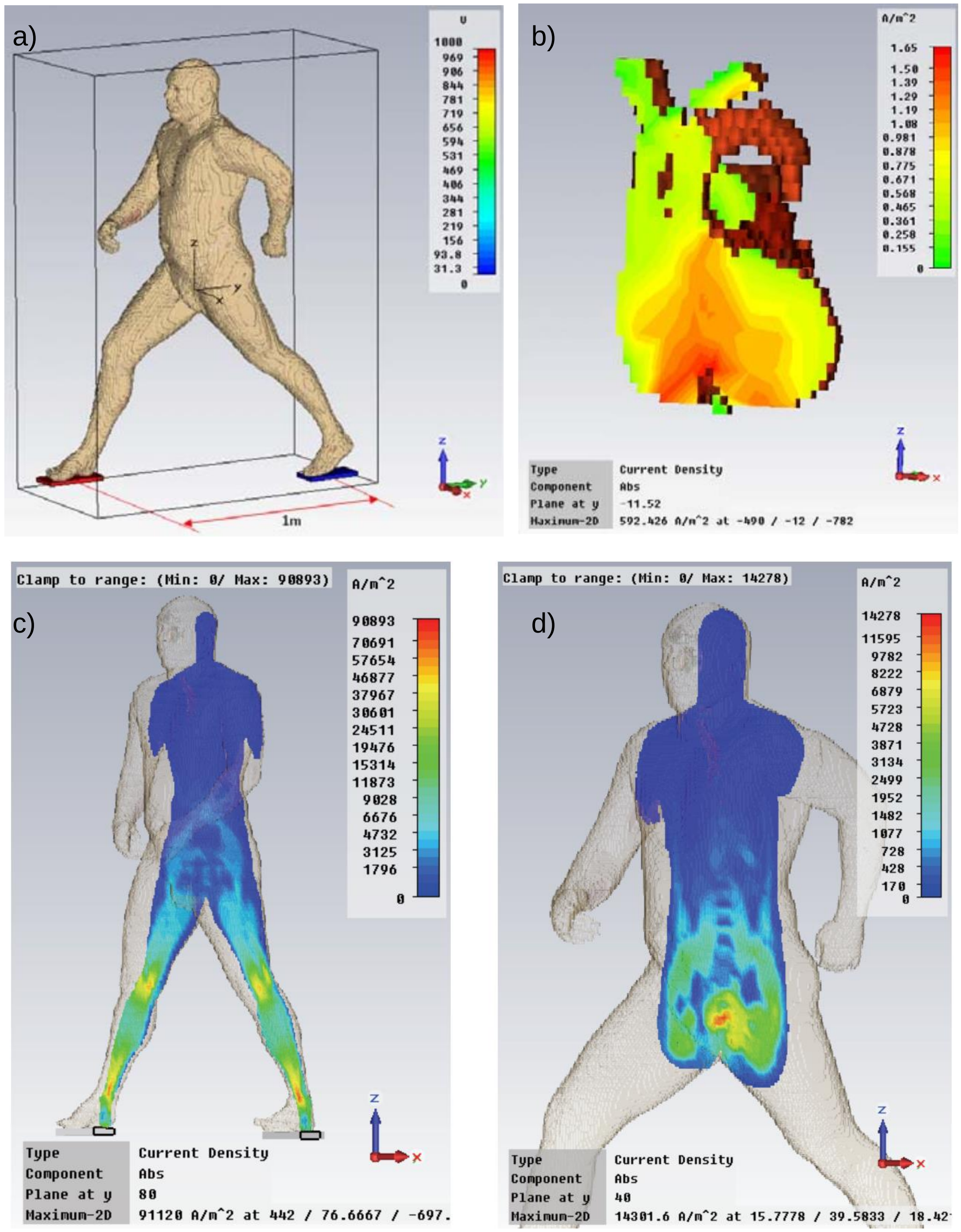


Figure 2-16. Hugo model (a) and current density for hearth (b), stand (c), and step (d) positions with contact surfaces at the base of the feet. Source: [101], [108].

2.5 Results and discussion

Lightning as source of injuries has several coupling mechanisms with humans and living beings, some electrical and others non-electrical. Lightning direct strikes are not the most dangerous mechanism, but currents diverted through the soil. Ground currents cause more than 50 % of all lightning-related fatalities, and together with side flashes and upward streamers mechanisms may be responsible for more than 90 % of all fatalities. Lightning currents can cause evident injuries such as wounds by burns and permanent disability, but also many non-obvious ones such as long-term neurological disorders.

Therefore, acting on the most severe lightning related injure mechanisms will help to reduce the lightning risk significantly and should always be considered. Despite the economic costs, it is feasible to reject the risk of loss of human lives and take all the measures that minimize it.

Models of the human body based on circuital impedances help to estimate values of currents for very basic and limited paths in some configurations, currently of interest for assessing the risk of electrocution and ECG analyses. As the human body is complex with many tissues with different electrical parameters, the voltage and currents inside the body are difficult to estimate to understand the effect of such currents in the health. The permittivity and electrical conductivity of the human tissues are frequency dependent and are different for each tissue showing that they are not linear, i.e., pure ohmic systems. Computer based models from digitized body (or parts of it) into small voxels, can reconstruct conditions in a more realistic and accurate way considering the different tissues with their electrical characteristics suitable for desired simulations.

Therefore, 3D computational models that consider electrical properties of tissues are more appropriate for simulating the path and intensity of lightning currents in the organism. Using the results of a Hugo model simulation, was possible to theorize that lightning ground currents have a strong risk in the fetal neurologic development when the head is turned down and placed in the current path, particularly close to the time of birth around the ninth month of gestation.

2.6 Concluding remarks

Among all known interactions between lightning and humans, the ground current mechanism is responsible for approximately more than 50 % of all lightning fatalities, being the most lethal. Despite the direct strike has been considered the worst lightning injury mechanism in the popular beliefs, actually accounting for about 3 % of all lightning-related deaths, surface flashover associated to direct strikes has been shown to have some protective effect by preventing currents from entering the body. This concept can be applied to personal lightning protection systems.

On the other hand, basic impedance models and computational models of the human body help from the rough assessment of electrocution risk to the analysis of the behavior of tissues against the spectral components of lightning currents and their paths inside the body.

3. Personal lightning protection – Case reports – Requirements

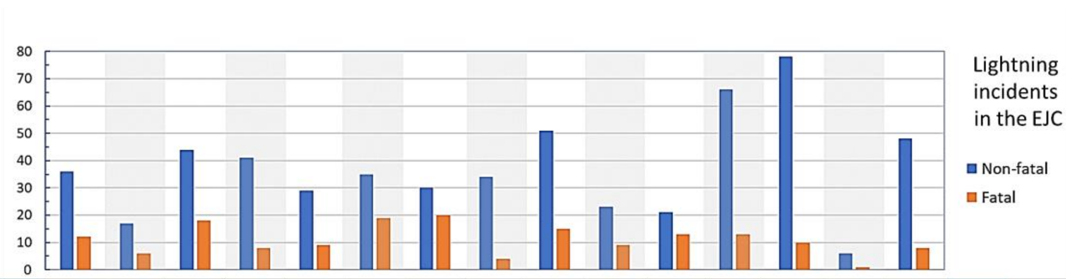
Most of the efforts to implement lightning protection have been made to protect buildings and structures such as places of habitation or gathering, historical heritage, and others of economic or special interest. Although the ultimate interest of lightning protection systems is to protect human life and its activities, there is a lack of information about personal lightning protection required in locations far away from typical LPS, bulk buildings, or any other effective lightning protection measure.

Many backcountry and "remote" places of the world are prone to high lightning activity where people develop their activities alone or in relatively small groups. It is desirable to have an easy-to-use and lightweight personal lightning protection system for use by National Armies and other security forces, agricultural workers and other isolated workers in temporary basis, outdoor sportsmen, and others. Numerous patents have been filed with lightning protection ideas, many of which have no technical or scientific basis beyond the application of some basic low voltage insulation concepts.

This chapter will briefly present some case reports and related information on lightning-human incidents of our authorship, where the effect of lightning coupling mechanisms on the human body is analyzed. Information on personal lightning protection measures taken from current technical literature, patents, other available sources, and from our research will be presented. Other information on the skin effect, the scope of lightning protection systems, and the justification for personal lightning protection will be discussed. Finally, the requirements for personal protection against lightning currents are proposed.

3.1 Reported cases of people struck by lightning

The Colombian National Army (*Ejército Nacional de Colombia* – EJC) is a population particularly affected by lightning strikes, with a relatively high number of personnel affected by this phenomenon, with consequences ranging from mild to severe and even death. The lightning-cause mortality rate for the Colombian Army population for 2005 was approximately 8.4 per 10 000 people, equivalent to 840 per million or 10 times that of Malawi (as shown in Figure 2-9). For 2008 it was 2.0 per 10 000 people, and for 2017 it was 2.4 deaths per 10 000 people. Figure 3-1 shows the reviewed annual statistics of lightning-cause injuries and fatalities in the Colombian National Army between 2003 and 2017 obtained from the Directorate for the Preservation of the Integrity and Security of the Colombian Army– DIPSE (*Dirección de preservación de la integridad y seguridad del Ejército de Colombia*) data.



Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total	Average/ year	Average/ month
Non-fatal	36	17	44	41	29	35	30	34	51	23	21	66	78	6	48	559	37.3	3.1
Fatal	12	6	18	8	9	19	20	4	15	9	13	13	10	1	8	165	11.0	0.9
Total	48	23	62	49	38	54	50	38	66	32	34	79	88	7	56	**724**	48.3	4.0

Figure 3-1. Statistics for lightning casualties at Colombian National Army (*Ejército Nacional de Colombia* - *EJC*) between 2003 and 2017. Source: data from DIPSE-EJC [91].

To put these figures in context, The Table 3-1 summarizes the average lightning deaths in EJC, and in the Latin America region between 2003 and 2014 according to data from "*Grupo de Eletricidade Atmosférica (ELAT) do Instituto Nacional de Pesquisas Espaciais (INPE)*" of Brazil [118].

It is interesting to see in the Colombian Army statistics (Figure 3-1) the change between 2015 and 2016, where for 2015 there is an increase in lightning incidents, while for 2016 the lowest level of lightning accidents and deaths was recorded. Both years 2015 and 2016 coincides with the crisis and final agreement of the peace process in Colombia, which consequently reduced the number of operations in the open field and therefore, the population exposed to the risk of being struck by lightning. This suggests that, as Professor Francisco Roman mentioned in an interview, "the best lightning protection for army population is peace".

Table 3-1. Lightning fatalities in 11 countries of Latin America region and Colombian National Army between 2003 and 2014.

Lightning Fatalities in Latin America Region 2003 - 2014 (1,2)		
Population / country	Average mortality rate fatalities/(10 000 people.year)	Average annual mortality fatalities/year
Colombian Army(2)	5.17	36
Cuba	0.059	65
Panamá	0.049	17
Perú	0.023	68
Colombia	0.016	74
Uruguay	0.015	5
Paraguay	0.009	6
Bolivia	0.007	7
Brasil	0.007	130
Venezuela	0.005	13
Argentina	0.004	13
Ecuador	0.003	5

Note (1) ELAT research data for 11 countries between 2000 and 2014
Note (2) DIPSE data related to the Colombian Army population of 2005 and 2008.

In the frame of this research work, based on own work and analysis of data and information of the DIPSE, two non-fatal lightning events in the Colombian Army and some of their effects were related, presented as papers at the International Symposium on Lightning Protection (SIPDA 2015) and at the International Conference on Lightning Protection (ICLP 2016) [39], [119], [120]. Also, the analysis of these two cases with some computer simulations were reported and published as a journal paper in the Electrical Power System Research Journal (EPSR) [69].

On the other hand, other two papers were presented. One of these two articles reports a case of multiple injuries caused by a single lightning event in the Sierra Nevada de Santa Marta - Colombia, and the other, an analysis of a case of trauma caused by lightning in a woman in pregnancy.

Section 2.3 has presented the known mechanisms of lightning-victims interaction related to the cases of the events discussed below.

3.1.1 Scenario analysis of two lightning survivors cases [39], [69]

In this work that was presented at a congress (SIPDA 2015, [39]) and published as a journal paper (EPSR 2017, [69]), two non-fatal lightning events in which the victims survived without obvious permanent disabling traumata are reported and discussed. Both events have important similarities despite having occurred in two places far from each other and at different times. The two victims were Colombian soldiers, and it was observed that the metal objects carried by the men intercepted the lightning currents leaving burns on their skin. It is quite possible that there was an interaction between these conductive objects and the indirect lightning currents, that could have maintained a pathway for the lightning currents on the outside of the victim's skin surface preventing them from entering and affecting the internal vital organs of the soldiers.

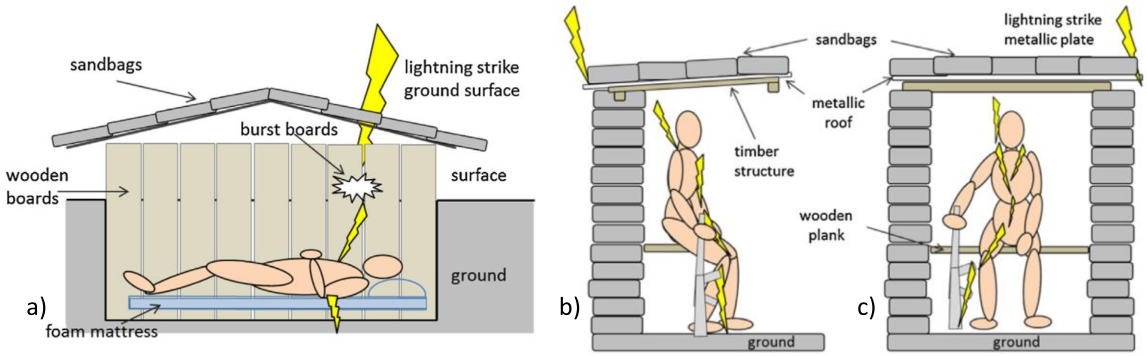


Figure 3-2. Schematics of the two reported cases where a) represent the dug-out shelter and b) and c) the hilltop sandbag shelter views. Source: [69].

It was shown that shelters dug into the ground, as well as ungrounded conductive roofs can allow the intensification of the electric field inside the shelter, enabling the inception of streamers that can follow as side-flashes. In both reported cases, the side-flash was the most probable coupling mechanism between the victims and the lightning currents. Considering this mechanism, the current could have been split and a part of it, passed through the victim's body. The large part of the current flowed through the metal accessories worn by the soldiers, some of which melted and burst, although it was only a fraction of the total lightning current.

As the lightnings strikes were not direct strikes in both scenarios, then, the diverted current that were coupled with the human bodies was even much smaller than the lightning channel could have been, but sufficient to melt the metal pieces. Therefore, the reported cases show that it is possible to divert dangerous high-level lightning currents away from the body to minimize the health risk.

3.1.2 Lightning strike with multiple injured in the Sierra Nevada de Santa Marta – Colombia [26]

The tragedy caused by a single lightning flash on October 5th, 2014, in which 11 indigenous people died and 15 were seriously injured inside a ceremonial house was analyzed from a technical point of view to know the most probable causes. 40 men were gathered inside an

Unguma, a large traditional ceremonial hut-style building made of flammable natural materials and thatched roof, on a stormy night when a lightning struck one of its two central poles. According to the tribal chief who was leading the meeting, the lightning caused a central column to explode, sending splinters into the air, one of which struck him in the face. It is probable that the stroke started a fire in the upper part of the thatched roof and the current crossed from the pole to the ground. Therefore, the main interaction mechanism that could have caused the tragedy was described as ground-currents, causing keraunoparalysis between other effects, preventing some people from escaping the fire.

Using electromagnetic computer simulations of a lightning strike in a simplified model of the ceremonial house, the ground potentials were calculated to estimate the energy through a basic human body model located at eleven places inside the building. The safe limit value of 20 J tolerable for the human body, suggested by Dalziel's experiments [28], [42], [121] was exceeded close to the stuck poles for different resistivity soil values.

It was remarked that prevention is the best measure to reduce the lightning risks. However, awareness alone is not sufficient to reduce lightning risk [40], [122]. Awareness and warnings may be useless if safe places are not available [40]. Unfortunately, there are many dwellings and human activities particularly in backcountry and faraway places, that permanently expose people to the risk caused by lightning.

3.1.3 Lightning-caused traumas in a woman in pregnancy [51]

The case scenario was described initially by Galster, Hodnick, and Berkeley [123]. Other elements were taken from media and video reports. The event took place in New Mexico, in the southwestern United States (U.S.A.), one July at around 9:30 pm. A pregnant woman and her husband were standing near a tree at the front of a house, preparing to go inside because a thunderstorm was approaching, when a lightning flash struck them. The woman (22-year-old) was about to give birth to a female baby, as she was in her ninth month of pregnancy. The man was 32-year-old.

No major complications were found after the primary hospital assessment, beside slight tachycardia in the woman and in the well-developed fetus. On the next hour, the right flank and lateral thigh of the woman's skin showed transient Lichtenberg figures. After three hours an emergency cesarean section was performed, due to decreasing fetal activity and tachycardia. The procedure resulted in the birth of a live female baby. Magnetic resonance on her first and second day of life revealed diffuse cerebral dysfunction with abnormal activity, diagnosed as a diffuse cortical injury without history in her family. For feeding, the baby required the placement of a gastrostomy tube.

After a week, the woman was still feeling pain in her calves and spasms in her lower back. The man still had not regained hearing in his left ear and needed a cane to stabilize himself due to vertigo attacks. After one year of follow-up, the baby had marked developmental delays, unable to sit, crawl or swallow, and still required a feeding tube. A subsequent neurodevelopmental assessment of the girl at 4 years and 5 months of age revealed profound global deficits that predicted severe permanent disability [124].

Some Gao's results presented in the paper [101] were used in our study about this lightning-caused trauma case [51], where was hypothesized that the position of the fetus's head at nine-month inside the womb and the lightning currents between both feet of the pregnant woman causes a permanent disability in the baby. It was shown that pelvic area, around the bladder maybe the most probable area of the body to occur a serious injury as shows the highest values of current density. Long term disabilities manifested by the born baby would be consequence of the intense electrical currents that disturb the normal development of the brain by altering the usual low level electrical activity.

The given hypothesis to explain the trauma, considering the fetal position according to the development inside the maternal womb is represented in Figure 3-3, showing the path of the current due to the difference of electrical potential between two feet by ground current, crossing the fetal head.

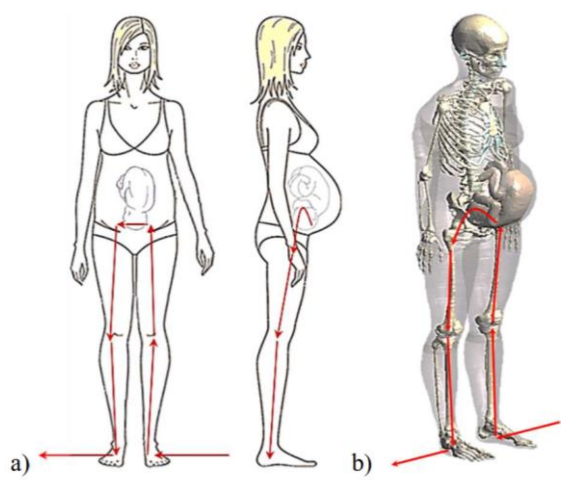


Figure 3-3. The path of the lightning ground current on a pregnant woman in her third trimester, close to the delivery time, is the most likely cause of permanent disabilities in the baby after birth. Source: [51].

3.2 Technological Surveillance

Considering the need for personal protection against lightning currents, several attempts to achieve this goal have been presented in the technical, scientific, and industrial literature, as well as in the media. Some of the principles used in these proposals are completely unaware of the extent of lightning currents and the real capacity of insulating materials against the intensity that such currents can reach.

A search for registered intellectual property protection was carried out through the patent databases Espacenet and Google Patents. The search criteria initially used yielded some results, some of which were considered to be supported by actual protection mechanisms and are presented in Table 3-2. The three most relevant patents for the purpose of this research are detailed below. The keywords used were: "lightning personal protection", "lightning protection clothing" and "lightning protection tent". In an additional search, other terms such as fabric, shelter, garment, thunder, wear, structure, and shock protection were included, yielding more than 7000 results. In general, it was observed that the related patents with personal lightning protection use one of two main protection approaches: (1) galvanic isolation of voltages associated to lightning currents and (2) Faraday Cage shielding protection, employing either highly insulating materials technology in the former, or technologies that employ good conductive materials in the latter.

3.2.1 Lightning protection proposals with a technical basis

Around 1970, J. Wiesinger developed a personal protective cage at the high-voltage laboratory of the Technical University of Munich (advised by Prof. H. Prinz). It consists of a wire mesh held by four supports that surrounds the person, even on the ground. The protective cage in the form of a tent could be disassembled and placed in a small and handy 4 kg package. This solution was investigated in the high-voltage laboratory in Munich under the conditions of the natural lightning current flow and was considered as a complete protection in the event of lightning strikes in the cage [125]. The development of this idea surely led to the patent application granted in 1970 in Switzerland as CH496869A *Notunterkunft, insbesondere Zelt* (Emergency shelter, especially tent) and in the USA as US3547136A Emergency shelter in the form of a tent or the like, with Expired – lifetime status. Figure 3-4 a) and b) shows two drawings from these applications patents. This proposal also considers a conductive base for the protection against step voltages.

Table 3-2. Representative worldwide patents related to personal protection against lightning.

Patent Info.	Abstract	Status
CH496869A, Switzerland US3547136A, USA 1970 Emergency shelter in the form of a tent or the like	A tent, or a shelter similar to a tent, where means are provided to protect the occupant, or occupants, against lightning bolts, which tent is in the form of a Faraday cage and the components constituting the cage are conductively connected to ground, or adapted to be connected to ground, and which generally comprises a metal frame and a cover that is preferably conductive for electricity and a metallic base or floor.	1970-12-15 Expired
DE102006057439A1 Germany, 2008 Lightning protection for individuals, integrated into clothing, tents and sleeping bags, comprises braided metal threads incorporated into fabric to form Faraday cage	A metal plait or braid is integrated into articles of clothing, tents and sleeping bags. The braid is made of steel fibers or other suitable metal. The braid runs along and transversely around the fabric. In this way a protective Faraday cage is formed.	2008-06-19 Withdrawn
CN101956481A China, 2011 Shielding Tents	The invention provides a shielding tent comprising a support frame and shielding fabric covering the support frame, wherein the shielding fabric internally contains compound fabric which is prepared by weaving copper, nickel and iron ternary superfine alloy metal fibers prepared from copper, nickel, and iron ternary superfine alloy granular metals through a chemical liquid phase deposition technique. Compared with the prior art, the invention has the beneficial effects of efficiently improving the shielding effect of the shielding tent on outside electromagnetic wave interference.	2011-01-26 Pending
US9301558B2 US, 2013 Cardiopulmonary lightning protection garment	A cardiopulmonary protection garment also includes a grounding member providing a movable connection between the conductive body shield and a local ground plane. Various configurations of the basic garment are contemplated, including a hooded jacket, hooded raincoat, padded vest, rain poncho, and the like. In various embodiments, the grounding member is a strap-like tail attached to the electrical body shield at an upper end and having a weighted lower end for maintaining a sliding contact with the ground. In other embodiments, the lower end is attached to a wearer's shoe.	2016-04-05 to 2035-02-05 Active
CN2707052Y China, 2005 Thunderbolt shielded garment for human body	Disclosed is a thunderbolt shielded garment for human body made of insulative materials of high resistivity and high breakdown field strength, which is characterized in that the head, the shoulder, the chest and the back of the thunderbolt shielded garment adopt double-layer structure; the connection region of the head and the body of the thunderbolt shielded garment and the connection region of the two sleeves and the body adopt bonding structure, and the bonding parts are connected through hot pressing. Matched with thunderbolt shielded footwear, the thunderbolt shielded garment for human body of the utility model can effectively prevent lightning attack. The utility model has the advantages of low cost of materials and easy bulk production. For the user, the thunderbolt shielded garment for human body can simultaneously functions as raincoats.	2005-07-06 Expired
JPH06235103A Japan, 1994 Thunder-proofing wear	PURPOSE: To provide a wear excellent in clothing comfort, making a body action ready and free, making it possible to move freely and capable of reducing the damage caused by a thunderbolt. CONSTITUTION: This thunder-proofing wear 1 is composed of plural pieces, i.e., a jacket 2, pants 3, a hat 4, gloves 5, socks 6 and shoes 7 as a footgear and the respective pieces 2 to 6 and the shoes 7 are each made of a conductive material. The respective pieces 2 to 6 and the shoes 7 are mutually connected through conductive connecting members 9 to	1994-08-23 Granted

Patent Info.	Abstract	Status
	13. The resistance and the inductance from the top of the thunder-proofing wear 1 to the other end part thereof are controlled respectively to ≤50mΩ and ≤1μH.	
JP2010522281A Japan, 2010 To prevent electric shock clothing	The present invention relates to integrated protective overalls for working on high-voltage lines in the current supply (5), this protective overalls comprises a first conductive layer, the surface area is the surface area of the overall (5) approximately equal, are obtained from coated polymeric fibers in silver. Overalls of the present invention may also include a second layer that is stably connected to the first layer.	2010-07-01 Pending
CN204169092U China, 2015 Lightning protection raincoat of new structure	The utility model belongs to the technical field of garments and relates to a lightning protection raincoat of a new structure. The lightning protection raincoat comprises a round cap, long sleeves and raincoat bodies, the raincoat bodies are connected through zippers, and the zippers extend to the lower edge opening of the round cap from hems of the bottoms of the raincoat bodies. The lightning protection raincoat is characterized in that the natural sagging length of the two long sleeves is smaller than the length of the raincoat bodies, a raincoat main body formed by the long sleeves and the raincoat bodies comprises an inner raincoat main body layer, a cavity layer and an outer raincoat main body layer, an inflation hole connected to the cavity layer is formed in the hem of the bottom end of the raincoat main body, an air plug having the same pore diameter as the inflation hole is correspondingly arranged in a matched mode, and the air plug is in threaded connection with the inflation hole. Two metal membrane layers between the outer raincoat main body layer and the inner raincoat main body layer can effectively lead leaked electricity or thunder and lightning into the ground, and therefore people can be protected.	2035-02-05 Expired
US20150189925A1 US, 2015 Simplified cardiopulmonary lightning protection garment	A cardiopulmonary protective garment for providing limited protection from lightning is fabricated of a waterproof/breathable fabric, such as a Gore-Tex TM laminate or equivalent. The garment keeps a wearer's body dry and supports a lightning flashover event when moist or wet on the outside, protecting the cardiopulmonary system. Strips of an electrically conductive fabric, such as Shieldex TM or equivalent, can be attached in various arrangements on a posterior outer surface of the garment for igniting a rapid flashover. The conductive strips also provide attractive design details. In some embodiments, an inner heat shielding and flame resistant layer, made of a fabric such as NOMEX TM or equivalent, can increase protection against burning caused by lightning and a flashover. Other embodiments may include a grounding strap electrically connected to the conductive strips for carrying charge to a local ground plane, such as the Earth; a cape-like drape of water-absorbing fabric having an electrically conductive element attached to a posterior side in general alignment with the wearer's spine; and a water-proof backpack having electrically conductive elements positioned to promote rapid flashover.	2015-07-09 Abandoned
WO2019115569A1 International, 2019 Personal equipment for protecting against events attributable to lightning strikes	The invention relates to personal equipment for protecting against events attributable to lightning strikes, in particular for use outside objects provided with external lightning protection. According to the invention, there is provision for a foldable or rollable base made of a conductive material or a material having a conductive coating, which base has dimensions that, in the laid-out or rolled-out state, ensure that a person seeking protection is sitting, crouching, lying or standing on the base such that step voltages between body parts or extremities of the person are avoidable.	2019-06-20 Granted

It could be considered that other relatively recent patent, the WO2019115569A1 Personal equipment for protecting against events attributable to lightning strikes, may complement the previous one as claims that through a somewhat flexible base made of a conductive material or a material having a conductive coating, ensures that a person lying, crouching, sitting, or standing on that conductive base would be protected against step voltages.

The patent DE102006057439A1 *Integrierte Blitzschutzvorrichtung für Kleidung, Zelte und Schlafsäcke* (Integrated lightning protection device for clothing, tents and sleeping bags) was declared as related to lightning protection for individuals, integrated into clothing, tents and sleeping bags, comprises braided metal threads incorporated into fabric to form a Faraday cage. Figure 3-4 c) and d) shows the drawings of this patent. The braid, of steel fibers or other suitable metal, runs along and transversely around the fabric. In this way a protective Faraday cage is formed. This principle can be applied to closed clothing, tents, sleeping bags and to outdoor equipment. With an elastic metal mesh, the article is designed in such a way that people are protected from lightning. The patent (in disposal status) claims that "to avoid a lightning strike", thin metal strips or threads (preferably of stainless steel or other suitable metal) are sewn into the fabric lengthways and across [126].

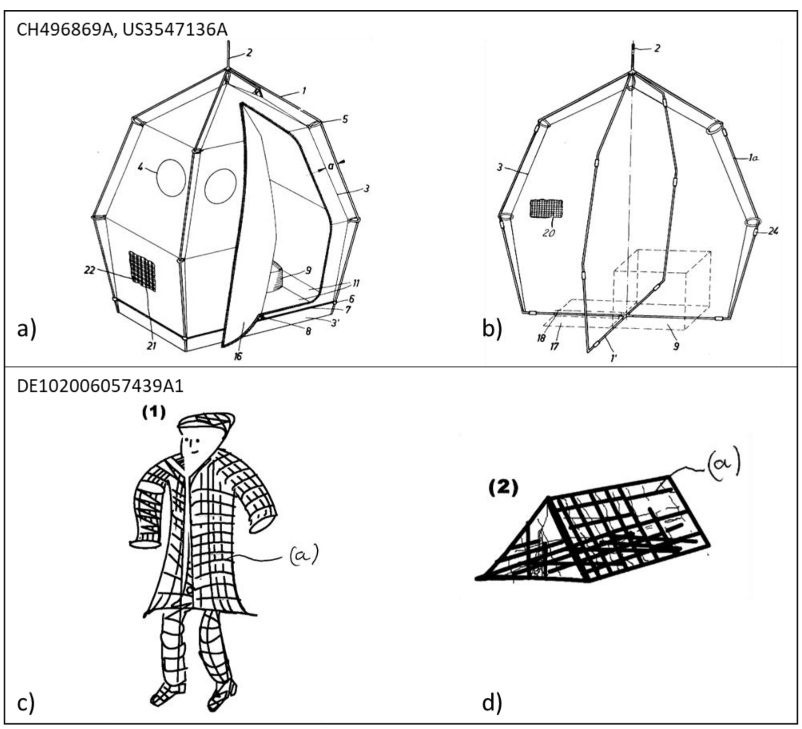


Figure 3-4. Drawings of the patents CH496869A (US3547136A) and DE102006057439A1. a) and b) depict a unipersonal shelter with an outside conductive frame with additional elements for comfort and weather protection. c) and d) represent a braid of steel or other suitable metal integrated into articles of clothing, tents and sleeping bags. Source: [126], [127].

Another patent, the No. CN101956481A Shielding Tents, registered in China with current status as pending, is a model of protective tents with conductive compounds weaving in the fabric (for example steel alloys, nickel, copper) through chemical deposition that improves electromagnetic interference shielding.

In an additional search performed in google search engine, other than the patent registrations, it was found that Polish Industrial designer Kamila Jania together with Konrad Sobolewski from Warsaw University of Technology (Politechnika Warsawska in Warsaw, Poland) designed, developed and performed some tests to a model consisting of an exterior lightweight metal structure that conducts lightning currents and would provide protection to occupants [128], [129], in similar way to the proposal of Patent No. CH496869A (US3547136A). Figure 3-5 shows images of this proposal that was tested in a high-voltage laboratory at 1 MV and with a high current surge generator up to 55 kA to simulate the effects of a direct strike.

Figure 3-5. Lightning protection tent designed by Kamila Jania and tested at the Warsaw University of Technology, that consider the conductive structure as a measure of protection. Source: https://www.designboom.com/design/kama-jania-bolt-tents-lightning-strike-protection-01-21-2016/

In 2018, two patents were granted to our research group (Electromagnetic Compatibility of Universidad Nacional de Colombia) for the development of protections against lightning for camping tents or similar and hammocks based on the Faraday cage concept, proposing the use of conductive materials, peripheral cables, and grounding rods to divert lightning currents to earth. In this way, lightning currents can be prevented from entering the body of the users. Table 3-3 shows some details of these two patents related to portable lightning protection, one for a tent and the other for a hammock.

Table 3-3. Universidad Nacional de Colombia patents related to lightning personal protection.

Patent Info.	Abstract	Status
15131006, Colombia 2018 Portable lightning protection device for camping tents (Dispositivo portátil de protección contra rayos en tiendas de campaña)	Corresponds to a temporary lightning protection tent or shelter in environments with unfavorable conditions of atmospheric electric discharges for populations exposed to lightning strikes, framed in high voltage engineering and in the so-called physics of gas discharge, specifically in the field of atmospheric electric discharges. The tent or temporary shelter adequately conducts the lightning current to the ground and prevents the current from circulating through the human body by means of a portable and lightweight device that acts on the principle of a Faraday cage, using conductive fabrics for indirect currents that do not have braided metallic conductors, but a multi-conductor peripheral cable for direct currents and tent support rods that also serve as grounding rods.	2018-02-06 Granted
15131009, Colombia 2018 Portable lightning protection device for camping hammocks	Corresponds to a transportable travel or camping article transformable into a stretcher or hammock to be assembled outdoors, capable of withstanding atmospheric discharges without prejudice to the user receiving any lightning strike, framed in high voltage engineering and in the Gas Discharge Physics, specifically in the field of Atmospheric Electric Discharges. The hammock properly conducts the lightning current to the ground and prevents the current from flowing through the human body by means of a portable and lightweight device that acts on the principle of a Faraday Cage, using conductive fabrics for indirect currents that do not have metallic conductors braided, but a single multiconductor cable for direct currents and grounding rods.	2018-02-06 Granted

3.2.2 Again, the Faraday Cage

The concept of a Faraday cage is commonly used for shielding purposes against electromagnetic fields in low power applications. In principle, the best lightning protection is provided by a Faraday cage around the target to be protected. Such a cage consists of a closed metal shell of sufficient conductivity, in which the target to be protected is enclosed.

It is known that common safest places against lightning are inside safe buildings or hard-topped metal vehicles [7], [38], [130] that divert the currents outside protecting inside acting as a Faraday cage. Safe buildings are those that have a sturdy structure and walls, able to safely divert the lightning currents, then, preferably with wire meshing, metallic framing, metal piping, or metal roofing connected to ground enclosing the space, better in a group of buildings.

However, theoretical perfect lightning protection provided by a perfect Faraday conductive structure with no discontinuities has limited practical value [7]. Nevertheless, this Faraday concept is used in some way by all the patents referred to in the previous section, regardless of gaps, penetrations, and windows that might ultimately limit its use.

Previously, in section 1.3.1, it was shown that mesh method with several down-conductors can be viewed as a Faraday cage. In addition, according to IEC 62305-3, the conductive steel reinforcement in concrete of a building form the “cage” required for the potential equalization of the internal LPS when used correctly [27].

To create a personal shield and provide protection when working at high voltages, metallic filaments and conductive wires can be used interwoven in complex shapes in a garment. Such a garment would provide a Faraday cage to the wearer so within it, any electrical potentials that might appear tend to zero and minimal or no currents are induced in the wearer's body. Thus, the interwoven conductive surface mesh can provide direct external paths for electrical currents around the body [131] in the way that was related in patent DE102006057439A1.

An interesting mathematical development of the Faraday Cage concept was done by Chapman et al. [132] particularly in a 2D model configuration where it is shown that the Faraday shielding effect depends, as expected, upon the number of wires and its diameter, but it is weaker than one would expect. The greater the number and diameter of the wires, the greater the shielding effect. Therefore, a cage with many small diameter wires covering the protection area could provide the same shielding effect as some larger diameter wires. If this is considered, together with the current-carrying capacity of the conductors, the objective of protecting against lightning currents would be fulfilled, allowing the use of flexible and lightweight materials as will be shown in this research.

3.2.3 Skin depth and electrical parameters

Inside electrical conductors, electromagnetic waves do not propagate uniformly on all the conductive material. On the surface of the conductor the current density is highest decreasing exponentially with the distance from the surface. Skin depth is considered as the distance from the surface at which the current density is reduced by e^{-1} of its surface value, that is approximately 37 %. Equation 8 gives the relation of skin depth δ for a good conductor [133] which can be rewritten as Eq. 9 showing the frequency dependance for a specific conductive medium.

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \qquad \text{Eq. 8}$$

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_r \mu_0}} \quad \text{Eq. 9}$$

where δ is the skin depth,

$\mu = \mu_0 \mu_r$ is the magnetic permeability of the specific medium with μ_0 the permeability of free space $= 4\pi \times 10^{-7}\ \mathrm{H \cdot m^{-1}}$, and μ_r the relative permeability which is dimensionless,

$\sigma = \rho^{-1}$ is the conductivity or the inverse of resistivity of the medium,

$\omega = 2\pi f$ is the frequency of the electromagnetic wave.

Lightning emits significant electromagnetic energy in the frequency spectrum from less than 1 Hz to about 300 MHz, with a peak in the frequency spectrum near 5–10 kHz [134]. This means that lightning current has several frequency components capable of causing damage in the human body tissues according to their electrical properties and frequency response. It is important to note that at the base of the lightning channel, the current can cause more damage at ground surface. Figure 3-6 shows the time domain signal and frequency spectrum of a standard lightning current waveform of a typical first return stroke with plotted components up to 5 MHz.

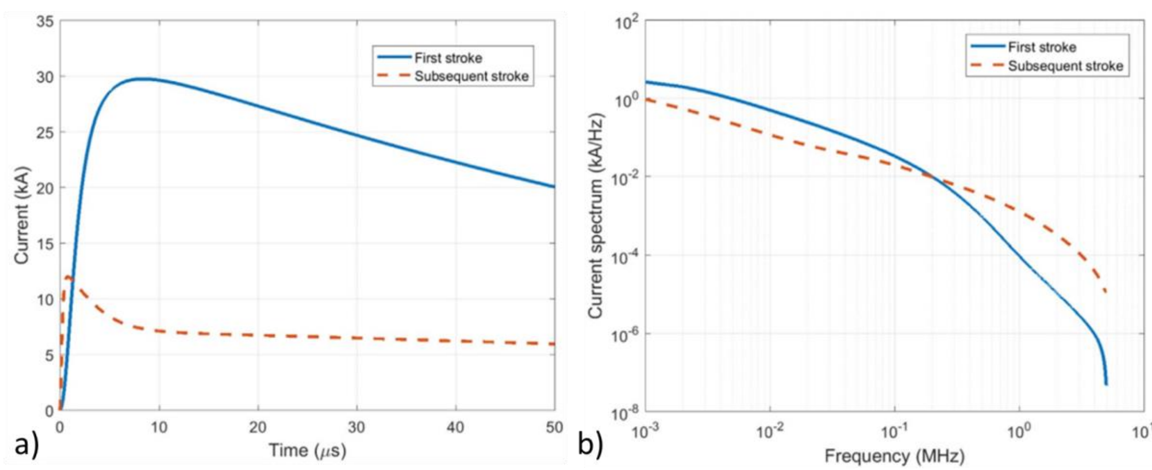


Figure 3-6. Time domain lightning waveforms a) and frequency spectra of currents b) for a typical first 30 kA and subsequent 12 kA return strokes at channel-base. Source: [135].

Many electromagnetic coupling calculation methods are based on frequency-domain analysis. When a single frequency is used for calculations, it is obtained by the sine wave that gives the same steepness (maximum derivative) and peak amplitude. This frequency is 124 kHz for first strokes with median 31.1 kA and 24.3 kA/μs. For subsequent strokes with median 12.3 kA and 39.9 kA/μs this frequency is 516 kHz [136].

Accordingly, the skin depth is an important concept to consider the materials to use in lightning protection and eventually in the human body models related to lightning currents.

Returning to Eq. 9 since skin depth is directly proportional to the resistivity ρ and inversely to the relative magnetic permeability μ_r, the lower the resistivity and the higher the permeability, the lower the skin depth. μ_r and magnetic susceptibility χ_m are related as show in Eq. 10 [133]. The units of χ_m are dimensionless and its data may be easier to find in material tables. Table 3-4 shows data of electrical parameters related to skin depth for copper, aluminum, silver, nickel, and an alloy with approximately 52 % copper and 48 % nickel, taken from materials properties tables or interpolated from them.

$$\mu_r = 1 + \chi_m \qquad \text{Eq. 10}$$

Table 3-4. Electrical parameters related to skin depth for four metals and a copper-nickel alloy.

parameter	copper	aluminum	silver	nickel	52Cu:48Ni
ρ [μΩ. cm]	1.673	2.655	1.586	6.840	50.000
μ_r	0.999994	1.000022	0.999800	600.000000	13.416000

from data and interpolation of [137], [138]

Figure 3-7 shows the log-log plot of skin depth (Eq. 9) for signal frequencies between 10 Hz and 10 MHz for the materials in the Table 3-4. Nickel shows an effect about ten times lower than the other materials considering its high permeability despite its higher resistivity.

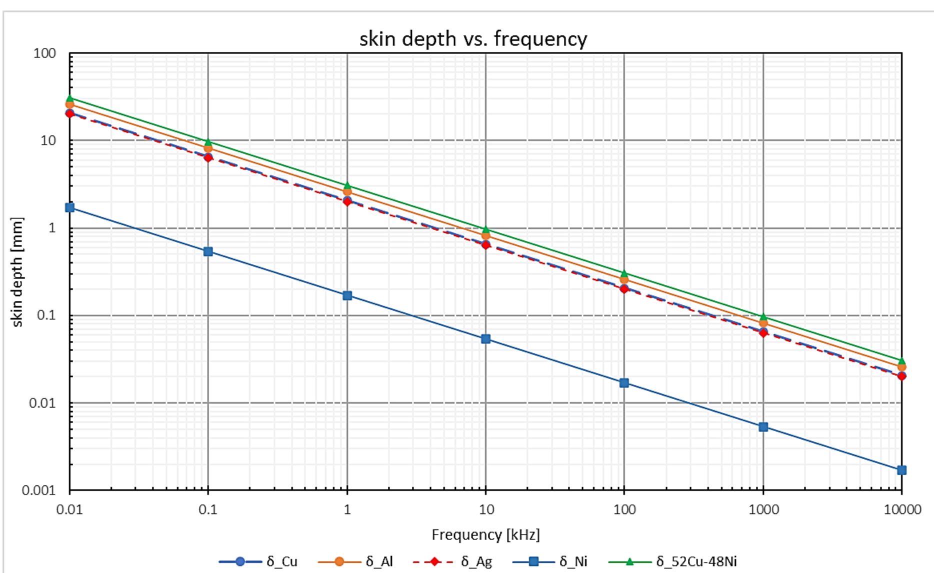


Figure 3-7. Skin depth vs frequency plot for four elements and a copper-nickel alloy (52%Cu:48%Ni). Source: author's estimation based on data from [137], [138].

3.3 Scope of any lightning protection

The former IEC 61024 standard stated that the primary function of a lightning protection system (LPS) is to protect lives and property from the destructive effects of lightning. The current IEC 62305-3:2010 standard sets out requirements for the protection of a structure against physical damage by a lightning protection system (LPS), and for protection against injury to living beings due to touch and step voltages in the vicinity of an LPS [27].

As shown in section 1.3.1, any basic lightning protection system (LPS) includes air terminals, down conductors, and a ground system. These elements are bolted or welded together to form a conductive path for lightning currents. A LPS can intercept lightning currents and direct them safely to the ground. The ground system consists of a conductive rod, set of rods, or a bare wire surrounding the structure to be protected, buried in the ground. This grounded “ring electrode” also equalize the potential on the ground surface and help to intercept electric arcs that could be produced along or under the ground surface toward the shelter from lightning currents outside the ring. If any of these three elements of a LPS is missing, the structure should be considered unprotected from lightning [139].

Thus, there is no fundamental difference between the scheme protection of people and the protection of structures [125] because in both cases the main function is to prevent currents from entering the protection target or inducing dangerous voltages.

However, for personal protection it is important to consider two main components of lightning currents: short and long duration components. The short duration components of lightnings are not necessarily lethal when interacting with human beings. Technical experience and medical observations show that current flow through the body is not necessarily fatal when lightning strikes a human being, particularly in lightning current impulses. Lightning accident reports and technical literature show that some conductive elements could help protect people from death by diverting currents and preventing a significant fraction of them from crossing through the body [7], [39], [61], [69]. External burn marks on the skin of the victims and in nearby objects suggest the formation of external sparkover with a protection effect as depicted in Figure 2-3. Paradoxical as it may seem, the sparkover can prevent death.

On the other hand, long duration lightning components, known as continuous currents, can maintain amplitudes of about 100 A for a few milliseconds to a few hundred, despite less common can cause death [7], [125] and a LPS must provide protection against them.

3.4 Justification of lightning protection for personal use

It is possible to perform a full risk assessment on any particular structure in any place to determine if a lightning protection is needed [7]. Therefore, a protection for personal use to minimize lightning risks must consider current statistics and knowledge related to lightning phenomena, in the way IEC62305-2 does, particularly to prevent human losses. However, in the lightning risk assessment, places with no very high lightning activity can easily exceed the tolerable limit for human losses even using warning systems intended to reduce the exposure time [118], [140].

Considering lightning maps only for continental lands of Colombia, most than 85 % of all places have a lightning activity above 8 strokes·km^{-2}·year^{-1}. About 20 % of all territory have a lightning activity above 64 strokes·km^{-2}·year^{-1} most in backcountry and faraway places with practically no lightning protection infrastructure. Now, considering the IEC 62305-2 to evaluate the lightning risk for that 85 % of the country, for a person working in open fields one third of his time and an indirect lightning stroke, the calculated risk for this person is about 320×10^{-5} per year, which is 320 times higher than the typical value of the tolerable risk for loss of human life or permanent injuries suggested in the standard (Tolerable risk R_T for L1 = 10^{-5} ·year^{-1}). Although “It is the responsibility of the authority having jurisdiction to identify the value of tolerable risk” [24], the risk value obtained is far from the tolerable risk, being totally unacceptable.

On the other hand, considering a lightning activity of 6.8 strokes·km^{-2}·year^{-1} for Brazil, supposing a person working in the open field that can be affected by a 20 meters away lightning strike, and who is also exposed one third of the hours of the year, the annual risk calculated for this person is 280×10^{-5}, which is 280 times greater than the acceptable risk, then, in most of Brazil people in the open are exposed to unacceptable risks related to lightning discharges [141]. The tolerable risk vs. the assessed risk, shows that many people in all the world are exposed to unacceptable levels, and it is necessary to implement any measures to mitigate that risk.

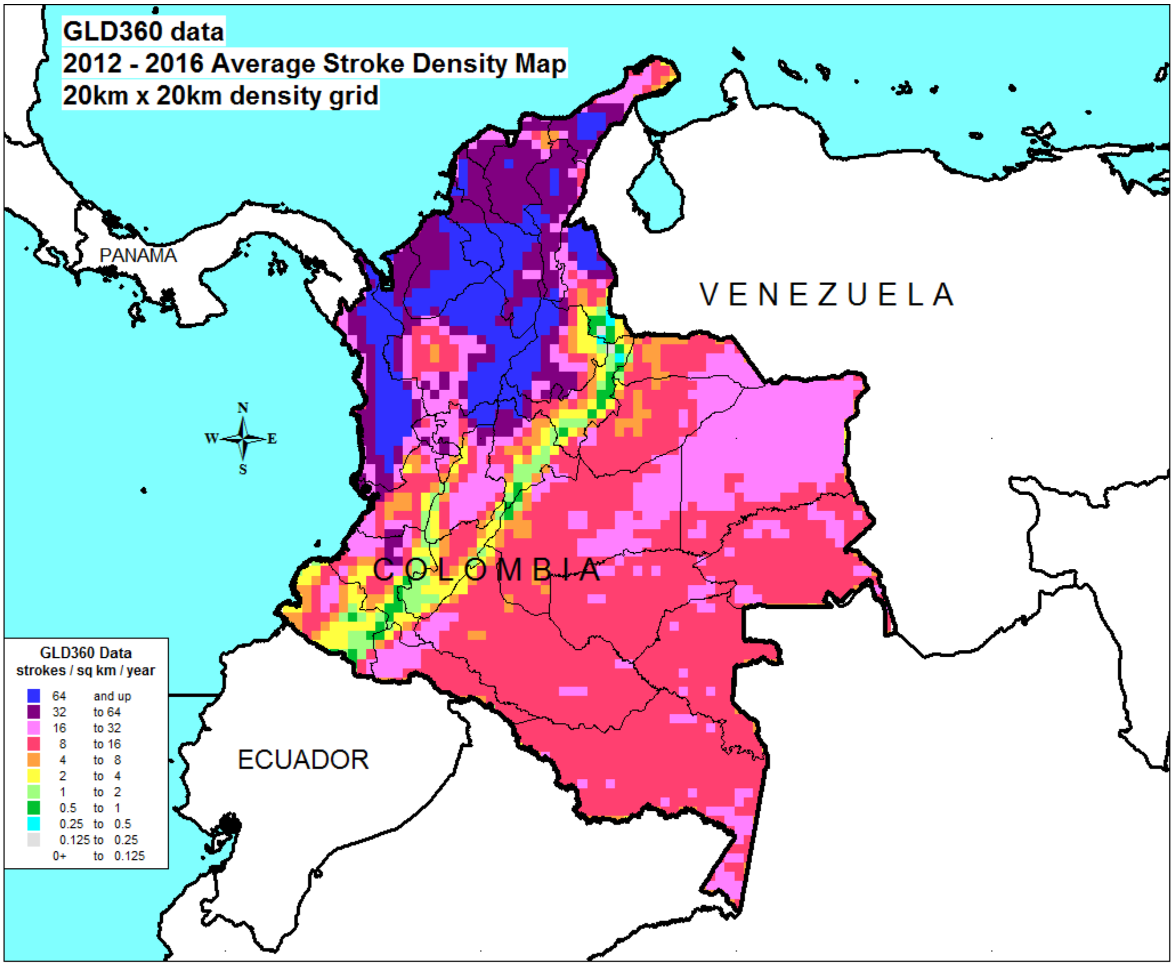


Figure 3-8. Lightning stroke density map for Colombia with a 20 km grid from GLD360 v2.0 of Vaisala dataset for 2012 to 2016. Source: Vaisala / R. Holle (personal communication).

We are of the opinion that any loss of life is unacceptable and therefore any measure that can be taken to reduce the risk is valuable. Where no avoidable risk is desired, any lightning protection measures should be taken regardless of the outcome of any risk assessment [24]. A portable personal lightning shelter could reduce the risk of lightning strikes.

3.5 Basic requirements of lightning protection for personal use

Prevention and planning should always be kept in mind as primary measures of lightning protection. "If people would plan ahead, keep an eye on the sky and get to a safe place sooner, there could be many fewer deaths and injuries" says John Jensenius, a lightning safety specialist with the NOAA [76].

On the other hand, there are some signs that may warn of the imminence of a lightning strike that cannot be ignored such as hair standing on end and tingling skin. In this case, shelter should be sought immediately. If that's not possible, it is recommended to adopt a squat position [94], [142], preferably on the tips of the toes with both feet joined together, minimizing the contact with the ground and becoming the smallest possible target. According to numerical simulations, that position can reduce the lightning exposure to a direct strike and to an aborted leader by 50 % and 70 % respectively [142]. In many human activities in faraway and backcountry places, it may be not possible to leave the area, so having a personal lightning shelter would further reduce the risk.

Considering the multiple cases of materialized catastrophic risk caused by lightning, some of them referenced in this work, the primary lightning fatalities as the most dangerous coupling mechanisms, statistical data of lightning activity by time, season, and place, existing alarm and warning systems, the availability of advanced lightweight materials with good electrical properties, it is possible to formulate some basic requirements for lightning protection schemes intended for personal use in remote locations far away from reliable lightning protection systems as follows.

I. Lightning Safety Training

1. Study, learn about lightning hazards and be prepared.
2. Read and understand lightning risks, injuries, and known injury mechanisms.
3. Consider all safety information available from reputable sources such as the National Weather Service of NOAA, or the ELAT of INPE from Brazil.
4. Since conventional lightning protection is not available in the open field, always keep in mind the 30-30 rule: the first 30 refers to the seconds from the time lightning is seen until its thunder is heard at the beginning of a thunderstorm. If the count is 30 seconds or less, lightning is about 10 km distant or closer, indicating that a person is in danger and should seek safe shelter. The second 30 s refer to the time elapsed in minutes to reach the end of the storm after seeing the last lightning or hearing the last thunder and the person must remain sheltered [38].
5. Be trained in first aid and cardiopulmonary arrest resuscitation (CPR) techniques.

II. Plan before outdoor activities,

6. Be informed well in advance and adequately of the historical lightning activity at the site for the season, month and throughout the day. Avoid travel, trips, and activities

in open places with recognized lightning activity moreover if it is an area close to lightning hotspots.

7. Avoid thunderstorm weather. Check and take advantage of lightning information tools and weather reports before the displacement to the target location. Consult current weather forecasts of the site you plan to visit and modify your plans if necessary.
8. Consider the environment, geographical factors, and the safest places, avoiding dangerous ones according to primary lightning fatalities mechanisms.

III. During unavoidable activities in open field and backcountry places [63], [143]–[145]

9. With thunderstorm developing, approaching, or clearance, avoid or leave places with increased risk such as mountain tops, ridgelines, tall and isolated trees, water bodies (creeks, boggy grounds, rivers, lakes, seas, and their beaches), caves, cliffs, and rocky overhangs.
10. Do not stay in shelters with ungrounded electrically isolated metallic roofs (such as sentry boxes, newsstands, kiosks, gazebos, and sheds) as they are not safe against lightning discharges [69].
11. Stay away from metallic fences, long conductors, and other conductive structures. Also, stay away from wet items (such as ropes) that can conduct electricity.
12. In the event of signs that may warn of the imminence of a lightning strike such tingling skin, hair bristle or standing on, crackling sound or unknown buzz, or ozone smell, adopt a squat position a.k.a. lightning position: sitting or crouching with knees and feet close together to create only one point of contact to avoid ground potentials. Use an insulating material as the base can reduce the ground potential rise effect.
13. Do not lie on the ground.
14. Some type of personal lightning shelter would be desirable to further reduce the risk of injury from lightning strikes. Although a lightweight shelter is desirable, if available, a vehicle with metal roof and frame or a metal cargo container [122] can serve as lightning shelter.
15. Select a suitable campsite to install the shelter based on the terrain conditions and the lightning knowledge to reduce the risk of being affected by direct or indirect lightning currents. Avoid exposed open fields, top of hills, ridge tops, water, or flood-prone areas.

16. If possible, it is advisable to divide groups of people into smaller ones and spread out about 30 m from each other.

IV. Basic requirements for personal lightning shelters

17. At least, the shelter must protect against the more lethal lightning effects: ground currents (a.k.a. step potential or earth potential rise), side flashes, and upward streamers.
18. The shelter must divert the lightning currents away from the body.
19. Suitable dimensions for at least one person to be protected from the elements (sun, wind, rain, etc.) and the lightning currents.
20. The shelter must be lightweight and portable.
21. The fabric of the shelter must be tear-resistant, withstand heavy use, harsh environmental conditions, and weathering.
22. Easy, fast, and convenient to set up.
23. Although laboratory experiments cannot fully simulate the conditions under natural lightning [6], [146] at least the shelter model must be tested under standard laboratory conditions with standard lightning current waveforms.

3.6 Results and discussion

Prevention is always the pinnacle measure of personal lightning protection [25], [26], [38], [40]. However, as the exposition to lightning risk is unavoidable for many human activities developed in far away and backcountry places with lightning activity, such as in the Colombian National Army, in agricultural works, and in some sports, it is desirable to have a personal lightning protection system. Many patents filled to attempt personal protection against lightning currents in outdoor conditions highlight the interest in and need for such a protective measure, which is not covered by current lightning protection standards.

As there are not lightning protection systems for people exposed in outdoor areas, the better solution to avoid lightning injuries and death in thunderstorm conditions is to follow procedures that take away people from open areas and put them into protective structures or shelters. IEC/TR 62713:2013 deals with safety measures for risk reduction outside large structures [43] but does not consider the use of appropriate shelters for the unavoidable outdoor human activities that demand them.

Any avoidable loss of life is unacceptable, and any measure taken to reduce the risk is worthwhile. All lightning protection measures should be taken regardless of the outcome of risk assessments. Even in relative low lightning-activity outdoor locations the risk is not taken seriously until it materializes. As it was shown, even in developed countries or in unlikely places as dug-out shelters, the lightning currents together with lack of prevention can cause permanent disability, death or social stress. Any technical or scientific-based measure to avoid the coupling of lightning currents with human beings can contribute to reduce the risk and its consequences. It is important to consider all potential causes of damage such as the skin depth of lightning currents, to consider the most suitable materials to use in lightning protection and, eventually, for the human body models related to lightning currents.

There is no fundamental difference between lightning protection of people or structures as in both cases the objective is to prevent exposure of the target to dangerous voltages or entering currents. However, protect human beings in outdoor condition with reliable lightning protection systems must involve the training, planning, and taking of measures to minimize unavoidable risks.

3.7 Concluding remarks

There are many tools to help to reduce the lightning risks such as lightning maps, lightning early warning systems, awareness and training, weather forecasts, and statistical analyses. However, these devices are not enough to minimize lightning risk in far away and isolated locations. Awareness and warnings may be useless if adequate shelters are not available. A portable personal lightning shelter could further reduce the risk of lightning strikes even more if proper prevention measures are taken including education, planning and the use of all tools and measures to avoid “avoidable risks”.

4. Proposal of a lightning protection system for personal use

To propose a lightweight and portable lightning protection shelter for personal use in outdoor conditions according to the presented basic requirements, some lightweight materials that could be used as part of a lightning protection system were investigated. Electroconductive fabrics (ECF) are textile materials with the ability to conduct electrical currents with the advantages of fabrics such as flexibility, strength, and low weight. A brief introduction to the types of electroconductive fabrics will be presented below. As will be shown, the very low resistivity of some electroconductive fabrics (ECF) is an important characteristic for their potential use as part of lightning protection systems.

Considering that ground currents is the most dangerous injury mechanism caused by lightning strikes, the electroconductive fabrics could help reduce the potential rise by being used as an equipotential surface forming a Faraday cage. To evaluate this, some electroconductive fabrics with interesting electrical characteristics were tested in Laboratory by applying several 8/20 μs standard currents on samples of these materials. Although nature's current wave shapes very rarely follow exactly a specified waveform, the 8/20 μs is a wave shape adopted by several standards to simulate and study the effects of lightning in the laboratory [6].

As a result of this work, a paper entitled "Lightning Impulse Current Tests on some Electroconductive Fabrics" was submitted to the *Journal of Applied Research and Technology* and accepted after a careful second round of peer review made by experts in the field. This accepted work, with a previous version uploaded to the arXiv and Hal pre-print repositories [147], [148], serves as a basis for this chapter with other also peer-reviewed papers published in several specialized congresses in lightning protection such as International Conference on Lightning Protection – ICLP and International Symposium on Lightning Protection – SIPDA.

The paper “Personal protection against lightning using electroconductive fabrics” submitted and presented to the ICLP 2022 describes laboratory tests done on a proposed lightning survival shelter made from an electroconductive fabric (ECF).

Finally, additional work related to tests on electroconductive fabrics is presented.

4.1 Electroconductive fabric types

There are several ways to weave textiles and to produce many types of electroconductive fabrics (ECF). The difference between ECF and ordinary fabrics is that ECF use conductive materials in the fibers and yarns of which they are composed. This will be discussed later. Meanwhile, some types of textile patterns used to manufacture ECFs will be presented below, with main information from [149] and laboratory observations.

Weaving. The process of interlacing two yarns so that they cross at right angles to produce a fabric. A woven fabric is composed of *warp yarns* in the longitudinal direction and *weft yarns* interlaced in the crosswise direction. The warp and weft yarns may be or not of the same type, material, and size. In the ECF each fiber of a yarn may have a core of insulating material coated with a conductive material, alloy, or composite. Figure 4-1 shows this type of fabric and others that will be presented below.

Knitting. It is a process of constructing fabrics by interlacing loops of one or more yarns. In warp knitting the yarns commonly run parallel to the selvedges, lengthwise in the fabric.

NonWovens. They are fabrics that are broadly defined as structures forming sheets or webs, bonding together separate fibers or filaments (and by perforating films) mechanically, chemically, or thermally. Fibers forming a non-woven fabric may be randomly oriented throughout the fabric or in a particular direction. To achieve improved strength, elongation, or any other mechanical properties, multiple layers can be combined. By varying fiber diameter, density, orientation and additional mechanical processing, porosity can be controlled.

Hybrid. As the name suggests, hybrid fabrics include more than one type of structural fiber in its construction into one or more layers. For example, in a woven hybrid fabric one fiber may run in the warp direction (longitudinal) and a second fiber type in the weft direction (crosswise). In each warp or weft direction it is also possible to use a combination of different fiber types. Although hybrid fabrics are most found in knit fabrics, this process is also used in non-woven, weaving, and braiding fabrics. Typical hybrid combinations in medical applications include Polypropylene/Polyglycolic acid, Polypropylene/Polylactic acid, and Polyester/Nitinol [149].

Braiding. A braid is a complex pattern formed by intertwining several strands (three or more) of flexible materials such as textile fibers or wires. Generally, the braids are long and narrow, with each component strand equivalent to zigzagging through the overlapping mass of the others. Complex braids can be formed from an usually odd number of strands to create a wider range of structures (such as wider ribbon-like bands, broad mats, hollow or solid cylindrical cords) [149].

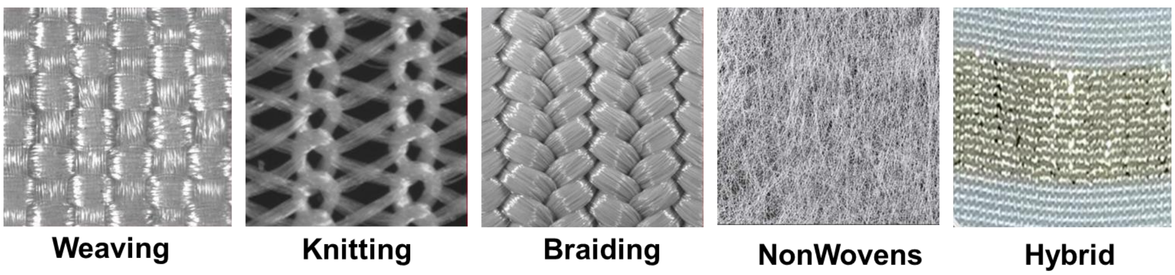


Figure 4-1. Optical micrographs of five types of textiles that can be used for electroconductive fabrics. Source: adapted from atextechnologies.com [149].

Table 4-1 below summarizes some key characteristics of textiles that can be found as electroconductive fabrics. Depending on the materials and processes used to manufacture non-woven fabrics, they can be somewhat fragile and brittle or, on the contrary, very strong, depending on the application. Woven fabrics without any special pattern and especially knitted fabrics can easily fray, unraveling the cut edges.

Table 4-1. Some key characteristics that can be found in electroconductive fabrics.

Fabric type	Characteristic					
	Dimensional	Flexibility	Elongation	Porosity	Strength	Fabrication
Woven	stable	medium	low	controlled	high (warp and weft)	easy
Knitted	flexible	high	controlled	controlled	easy unraveling	medium
Non-woven	stable	low	low	controlled	medium to low	easy
Braided	flexible	high	high	controlled	high	complex

4.2 Lightning impulse current tests on electroconductive fabrics [1, 2] [147], [148], [150]

On the search of lightweight lightning protection materials that can be used as part of Lightning Protection Systems (LPS), we investigate some types of electroconductive fabrics by applying several lightning impulse currents in laboratory. Samples of four commercially available electroconductive fabrics were analyzed: two rip-stop, a plain-weave, a nonwoven, and additionally a carbon-impregnated polymeric film. Under laboratory conditions, each sample was subjected to several lengthwise subsequent lightning-like currents of 8/20 µs waveform, recording both voltage and current signals. Optical and scanning electron microscope observations were performed after tests, revealing some patterns or morphological changes on the fabric surface. Despite these changes, the investigated conductive fabrics withstand the several lightning impulse currents applied. Results suggest that some conductive fabrics could be used in personal mobile shelters, to protect human beings against the earth potential rise caused by a close lightning discharge.

4.2.1 Introduction

The uneven distribution of lightning activity on the planet, as shown in the global lightning maps, let in evidence that some places in the world have very high levels of lightning activity. In these places, the population could be more prone to suffer injuries caused by lightning. The top 100 places of the world with the highest lightning activity have a lightning density in a range between 83.45 and 232.52 flashes $km^{-2}a^{-1}$ [1]. Many fatal accidents show that people who are involved in outdoor activities or open fields are more vulnerable to the risk of lightning strikes, as reported both in the media and in technical literature. [69], [151]–[153].

To reduce the risk of death caused by lightning strikes on living beings and damage in structures, buildings, installations and their contents (IEC 62305-1 2010), several techniques intended to intercept direct lightning flashes and to conduct and disperse their currents safely into the earth have been developed [28]. To mitigate the aforementioned

[1] Authors: J. A. Cristancho, J. E. Rodriguez, C. A. Rivera, J. J. Pantoja, L. K. Herrera, F. Román.

[2] A preliminary version of this paper was uploaded in the pre-print repositories arXiv and Hal [147], [148]. The paper entitled "Lightning Impulse Current Tests on some Electroconductive Fabrics" [150] was published and available on 2023-04-30 in the *Journal of Applied Research* JART, submitted on 2021-05-13, and accepted on 2022-09-22.

lightning threats, a lightning protection system (LPS) must be the capability to effectively capture and safely divert hazardous lightning currents towards the ground. For fixed external building protection, the IEC62305 and NFPA 780 standards [19], [154] recommend the use of some materials and components that in most of the cases are heavy and bulky. Nevertheless, in some outdoor, faraway, backcountry or not easily accessible locations, the use of weighty materials and equipment is almost impossible, constraining the possibility to have acceptable LPSs. This condition makes some human activities to be permanently exposed to the catastrophic risk of lightning.

In the research field of technical and industrial fabrics, the electroconductive fabrics (ECF) show great potential of application on several industries [155]–[157] but until now, there is a lack of information about their use in power or lightning applications. The electrical signals applied on ECF are low power rated, such as in electromagnetic interference (EMI) shielding applications [158] or in strain sensing applications [159].

In this paper, it will be shown that some ECF, subjected to high current impulses in the laboratory, could withstand natural atmospheric lightning impulse currents (LIC) enabling its use in personal lightning protection and power applications. Electrical tests and measurements were performed on some ECF, as well as microscopy observations to analyze the behavior of the fabrics when divert high currents. It is proposed a possible alternative use of some ECF as components of a lightweight LPS technology for use in tents, portable lightning shelters, and other power applications, stablishing some parameters that limits the current or energy level in the used fabrics.

4.2.2 About electroconductive fabrics

ECF are fabrics with the ability to conduct electrical currents, using conductive materials in their constituent fibers and yarns. According to the weave pattern they can be woven, nonwoven or knitted. Woven fabrics consist of interlacements of yarns in mutually perpendicular directions, interlacing or interweaving warp-and-weft yarns. On the other hand, nonwoven fabrics are produced by the bonding or interlocking of fibers with mechanical, chemical, thermal, or solvent methods, or combinations thereof [156], thus giving a random structure. Knitted fabrics are made up of a single yarn, looped uninterruptedly, producing a braided appearance. The weave structure, pattern and the number of yarns depend on the fabric type. Only woven and nonwoven ECF were used for this research. Figure 4-2a shows optical micrographs of four ECF utilized in this research, and Figure 4-2b a warp cross section of a rip-stop ECF (also used in this work), revealing 48 weft yarns of the fabric. Each yarn has an average 15 µm diameter with an outer conductive layer of about 1 µm thickness. Commonly in woven textiles, warp yarns are more stressed than the weft ones since the former are stretched to receive the interlaced ones of the latter.

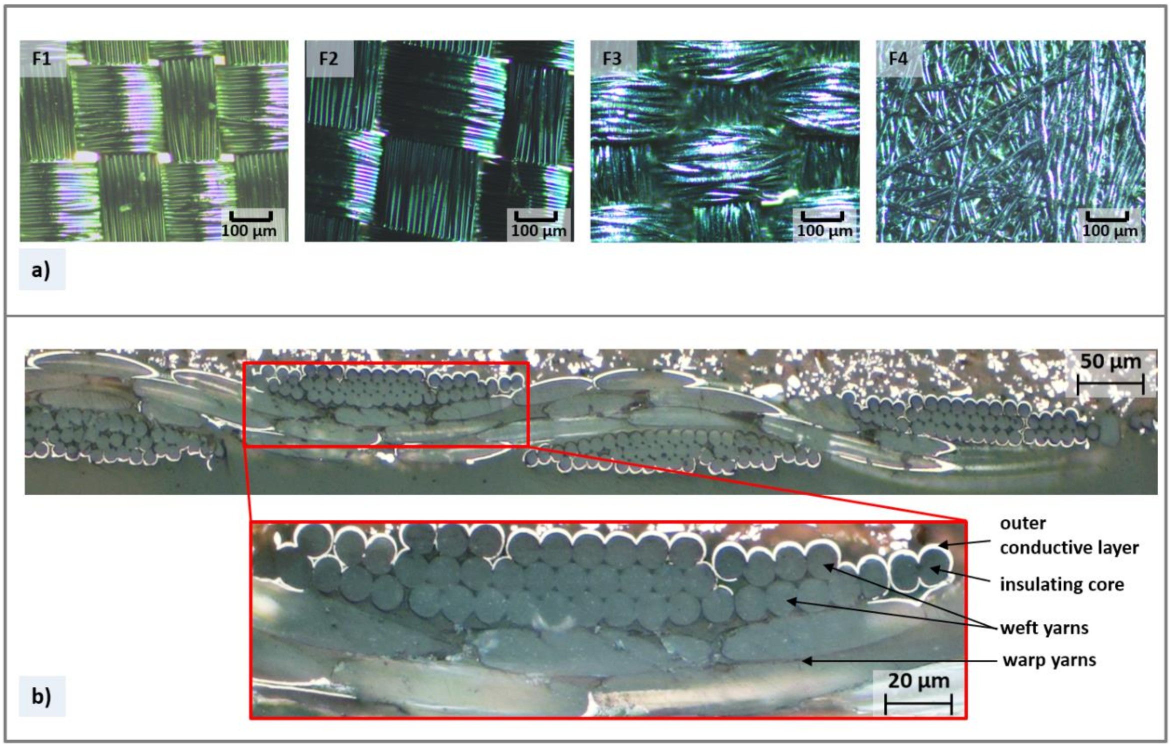


Figure 4-2. Optical micrographs of electroconductive fabrics tested in this research. a) Surface sample of four electroconductive fabrics where the color difference between F1 and other ones is due to an illumination effect; b) Warp cross-section of an electroconductive rip-stop fabric showing 48 weft yarns cramped along warp filaments, where in the zoomed image it is possible to identify some inner insulating fibers with their outer conductive shell.

4.2.3 Sheet resistance

ECF are not homogeneous structures with isotropic electrical current distribution. Electrical modeling of conductive fabrics is complicated, since the material must be treated as a combination of resistors in series and parallel connections considering the interlacing filaments [160]. An electrical model of the whole ECF could be treated as a very large-scale symmetric network of basic yarn interconnected sections. The entire model can be reduced to multiple single yarns connected in parallel [161] which in the end can be taken as a uniform conductive sheet. The electrical resistance of a full symmetric grid corresponds to that of the basic electric model, which mainly depend on the material, pattern, and geometry of the conductive elements. The electrical resistance value will also depends on several external factors, such as temperature, humidity, pressure or dimensions [160], [162].

Considering the conductive fabric surface as a thin film conductor [161], the sheet resistance is frequently used to refer to the electrical resistance of a full symmetric grid, i.e. a square of fabric independent of the side length. This is different from the bulk resistance used for wires conductor specification. Considering the regular three-dimensional resistance R of a conductor, Eq. 11 describes the mathematical model of the resistance for a conductor square of sides W and thickness t, in the direction of a current I, going through the cross-sectional area A.

$$R = \rho \frac{Lenght}{Area} = \rho \frac{W}{t.W} = \frac{\rho}{t}\frac{W}{W} = \frac{\rho}{t} \;\; [\Omega] \qquad \text{Eq. 11}$$

Eq. 11 is valid only for a square of film conductor, where ρ is the resistivity and $\frac{\rho}{t}$ is the so-called sheet resistance Rsh, then R is independent of the size of the squared sample [163]. Despite the unit of electrical resistance in the International System of Units (SI) is the ohm (Ω), in the conductive films industry it is commonly expressed in units of ohm per square (Ω/□ or Ω/sq) which expresses that the resistance is measured on a square of material of side *w* and it is independent of its side length [164], [165].

4.2.4 Overview of lightning impulse tests

A lightning flash to earth is an electrical discharge of atmospheric origin between cloud and earth consisting of one or more strokes [19]. Cloud-to-ground lightning effects depends mainly on the high current amplitudes developed when the unbalanced opposite charges between clouds and ground are neutralized. When a lightning strikes the ground directly or through a tall object, the currents are radially distributed on the earth in all directions from the striking point to the exterior. Despite of fact that lightning currents could reach more than 200 kA, for negative first strokes the global lightning median return-stroke peak current is about 30 kA and typically 12 kA for subsequent strokes [8]. For some countries such as Brazil, Colombia and Zimbabwe (former Rhodesia), the average lightning peak value is about 42 kA [8], [13]. Lightning current density diverted into the ground still hazardous to life and health even at distances of several meters from the strike point, although it is inversely reduced to the square of the distance.

Impulse voltages with front durations varying from less than one up to a few tens of microseconds are considered as lightning impulses [166]. To assess the effects of lightning currents over equipment and materials, standardized lightning-like impulse currents (LICs) are generated in laboratory to simulate natural lightning impulses.

Parameters of lightning impulses currents (LICs). The peak value I, the front time T1 and the time to half value T2 are basic parameters of the standardized wave shape typically used in laboratories to simulate the effects of LICs on lightning protection systems – LPS – components [19] as shown in Figure 4-3a. Commonly, in a lightning impulse the time T2 is less than 2 ms. For example, a current waveform 4/10 µs of 20 kA (or 20 kA 4/10 µs) refers to a surge of current of 20 kA peak with 4 µs of front time and 10 µs of tail time up to its half value.

When an electrical current flow through a resistive material, heating is produced due to the Joule effect. To estimate the energy dissipated by the ECF as joule heating due to each applied current pulse, the instantaneous power applied over the fabric should be considered. The following expressions Eq. 12 and 13 are used to evaluate the energy after each current impulse:

$$P(t) = V_e(t) \cdot I(t) = (I(t) \cdot R) \cdot I(t) = I^2(t) \cdot R \qquad \text{Eq. 12}$$

$$E = \int_{t=0}^{T} P(t)dt = R \cdot \int_{t=0}^{T} I^2(t)dt \qquad \text{Eq. 13}$$

where P is the power, Ve is the measured voltage between electrodes, I the current applied, R the resistance of the conductive fabric, E the energy, and t is the time.

4.2.5 Materials and methods

Fabrics used as samples under test. To determine the structural characteristics that provide conduction of high current levels, the objects under test (OUT) were samples of electroconductive fabrics with different weave types and manufacturing techniques: rip-stop (named as F1), rip-stop with a side layer coated with a flame-retardant UL94V-0 composite (F2), plain-weave (F3) and a nonwoven fabric (F4).

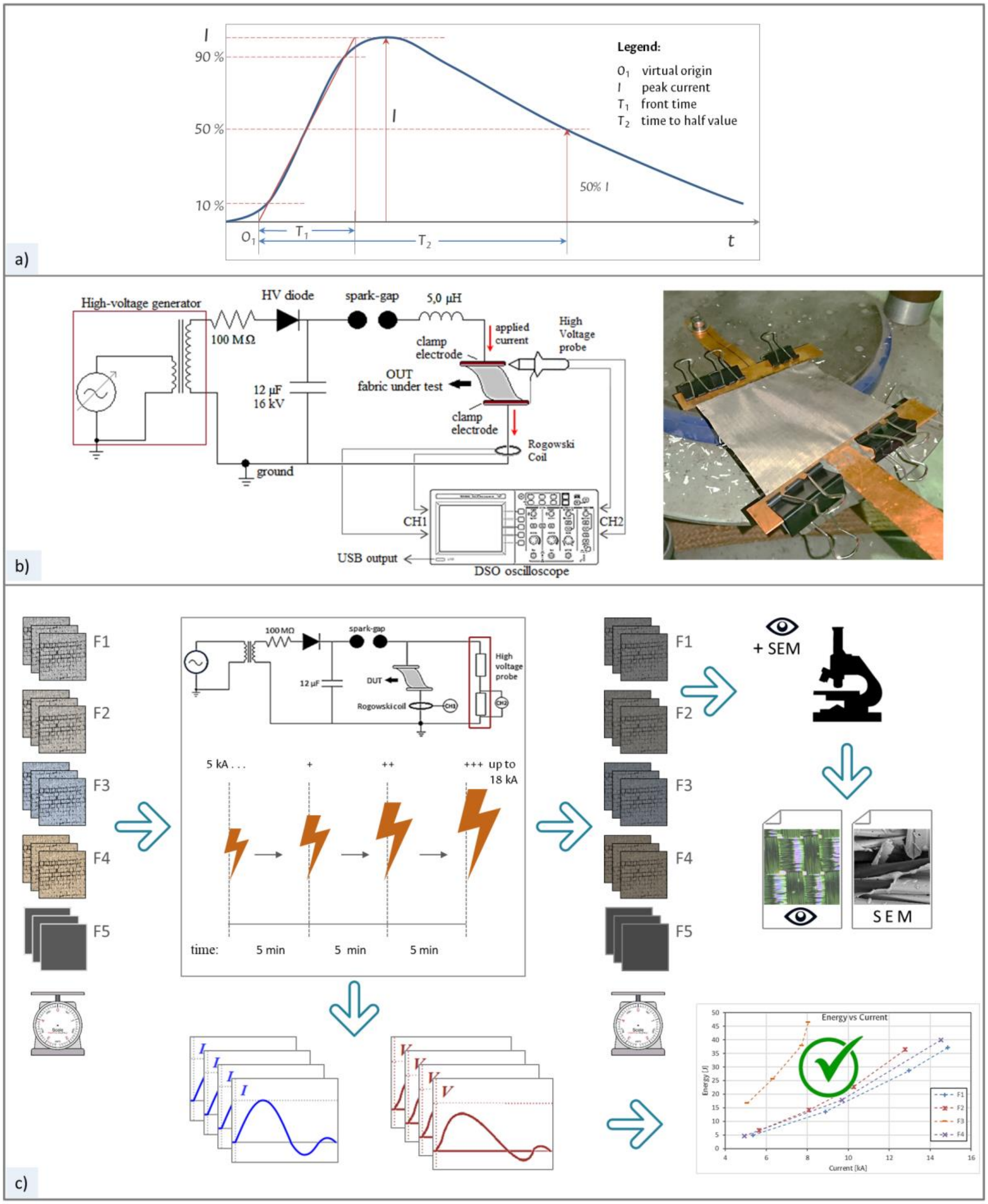


Figure 4-3. Experimental setup. a) Definitions of a laboratory standard lightning impulse current (LIC) signal with its parameters according to IEC 62305-1; b) test bench setup schematic of the Lightning Impulse Current Generator (LICG) used and a sample of electroconductive fabric fastened by the two copper clamp electrodes; and c) procedure for LIC tests over electroconductive fabrics and film.

In addition to these, a conductive polymeric film (F5) was tested. F1 to F4 are electroconductive fabrics (ECF) produced with yarns of the same characteristics by the same manufacturer. The material F5 is a polymeric film impregnated with carbon black from other industry.

Fabric types F1 to F4 were selected because the material type and weave pattern are easily available from different manufacturers in the market, broad commercial offer, low price (comparatively with other ECF), and wide use in electromagnetic shielding. Despite the material F5 is not a fabric or textile but a conductive film, it was tested to assess their ability to withstand lightning-like currents and compare it to that of conductive fabrics.

The structure of each yarn of the ECF follows the structure observed in Figure 4-2, made from fibers of an insulating polymeric core covered with a conductive material layer. The inner fiber is a monofilament made of polyester, constituting 65 % of the entire yarn. The manufacturer data sheet gives the composition of the remaining 35 % outer conductive layer as 57 % Cu - 43 % Ni alloy. The UL94V-0 level flame-retardant coating composite of the fabric F2, covers one side of a conductive rip-stop fabric of the F1 type. The main characteristics of the ECF samples are summarized in Table 4-2. Parameters of the tested electroconductive fabrics and film. The presented sheet resistance unit is given in ohm per square (Ω/□).

An optical microscope Olympus BX-41 with U-CMAD3 was used to observe the samples before all the tests. Also, a Scanning Electronic Microscope SEM Tescan Vega 3 SB, with secondary electrons (SE) and backscattering electrons (BSE) detectors, was used to observe some selected sections. In addition, the samples were weighed in an analytical Sartorius Entris 224I 1S balance scale.

Lightning impulse current generator setup. The LICs were generated by a Lightning Impulse Current Generators (LICG). 8/20 µs current waveforms generated by the LICG were used (T1 of 8 µs and T2 of 20 µs). High amplitude current impulses with that waveshape are considered standardized lightning impulse currents.

The schematic setup of the LICG is represented in Figure 4-3 b. By changing the distance between spheres of the spark-gap, it is possible to control the LICG charging voltage, hence the peak amplitude of the applied current pulses.

Table 4-2. Parameters of the tested electroconductive fabrics and film

Item	Unit	F1	F2	F3	F4	F5
Weave pattern	type	**Rip-stop**	**Rip-stop with FR** (a)	**Plain**	**Nonwoven**	**Polymeric film**
Areal density(b)	g/m^2	90.0 ± 10.0	245.0 ± 10.0	130.0 ± 10.0	90.0 ± 10.0	238.0 ± 10.0
Thickness(b)	mm	0.10 ± 0.01	0.16 ± 0.02	0.15 ± 0.02	0.08 ± 0.01	0.10 ± 0.01
Sheet resistance(b)	Ω/□ (c)	≤ 0.05	≤ 0.07	≤ 0.07	≤ 0.05	< 31000
Resistivity(b)	µΩ·m	≤ 5.0 ± 0.5	≤ 11.2 ± 1.4	≤ 10.5 ± 1.4	≤ 4.0 ± 0.5	< 3.1×10^6 ± 0.1×10^6
Conductive material	type	Ni-Cu	Ni-Cu (a)	Ni-Cu	Ni-Cu	impregnated with carbon black
Core material	type	polyester	polyester	polyester	polyester	polymeric-film

(a) Uses a side with a coating layer of Flame Retardant level UL94V-0 composite.
(b) The value after ± sign is the specification limit, and after ≤ or < sign indicates the upper limit of the specification.
(c) SI unit is the ohm, but the common unit used for the sheet resistance is the "ohm per square = Ω/□".

Current is measured with a Rogowski coil with integrator, and voltage with a High Voltage Probe with a 1000:1 ratio. To record these signals, the two channels of an Agilent DSO6104A oscilloscope with ground isolation are used. The ECF samples as objects under test (OUTs) are fastened by two copper clamp electrodes to provide physical support and electrical contacts between the current generator and the fabric sample, as shown in Figure 4-3 b. In this setup, the OUT must have enough low impedance to allow the conduction of the current impulse mainly because the resistance of the fabric sample is part of the LICG discharge circuit.

Procedure. The procedure for testing the ECFs against lightning currents is depicted graphically in Figure 4-3 c, conducted by means of a LICG over three samples of each four ECFs and one polymeric film similar to the methodology presented in [30]. Three squared pieces of 10 cm x 10 cm of the five materials Table 4-2 were trimmed identifying their warp orientation (fabrics F1 to F4 and the film F5). Each sample was named and marked according to its material followed by sequential number, e.g. sample F2-3 corresponds to a sample 3 of the fabric sample F2, and F5-1 corresponds to a sample 1 of polymeric film (F5). Optical microscopy and weighed of the samples were done.

Each sample, placed lengthwise to the surface of the fabric in the warp direction and connected to the circuit through copper clamp electrodes, was subjected to a set of at least four subsequent LICs, starting from 5 kA, increasing in leaps greater than 2 kA with time intervals of 5 minutes between each test.

Fabric samples are tested with consecutive 8/20 µs LICs, starting from 5 kA in increasing leaps estimated to be larger than 2 kA, up to the maximum current that the generator can drive with the actual impedance given by the fabric sample.

To observe and compare the impedance behavior of each ECF sample, it is measured and recorded both voltage and current signatures across the OUT on the clamping electrodes.

To investigate the variation of the conducting fabric's resistance after the application of successive LICs, this sub-procedure is followed: from the first 5 kA LIC recorded data, we only take the first cycle of both the measured voltage drop and the current. The maximum current value and its corresponding voltage datum are selected from this data set and the dynamic resistance is calculated by means of Ohm's law. The same sub-procedure is followed for each consecutive current test of each fabric sample. Then, it is calculated and tabulated the pseudo electrical resistances, and generated plots of voltage vs. current. In addition, the energy of the first positive semi-cycle of each applied LIC is estimated using equations (3) and (4) and the energy vs. current characteristic is plotted.

The polymeric film (F5) was also tested in a similar way but only with a first single LIC of 5 kA due to it ignited and melted along the test electrodes contacts before allowing other trials. For this, F5 is not studied like the fabric samples, and it does not appear in most of this paper.

After the LIC test, the samples were observed in the microscope and weighed again to compare the fabrics before and after the tests and to analyze how the fabrics were changed by the high current flow. Additionally, some small sections trimmed out from the samples were examined through the SEM Microscope, with an acceleration voltage of 20.0 kV, to increase the observation capacity for identify the structure of involved materials, and to get more details of the changes over the fabric surface. To estimate the change in the elemental composition of the surface, Energy Dispersive Spectrometry (EDS) analyses were performed over a sample of rip-stop conductive fabric (F1), before and after lightning tests.

4.2.6 Results and Discussion

Optical microscopy before tests. Figure 4-2a shows micrographs of the untested fabric samples. F1 and F2 correspond to rip-stop type, F3 to plain-weave type and F4 to nonwoven conductive fabric type. F2 has the back side coated with a flame-retardant composite that increases the temperature strength, as well as the fabric thickness, stiffness, and weight. The picture of the coated polymeric film F5 is not included in the Figure 4-2 since its homogeneous surface image does not provide significant information.

Lightning impulse current (LIC) tests. Figure 4-4 shows representative samples of each one of the ECF and the coated polymeric film after the application of the last LIC. Regarding to the F5 polymeric film (Figure 4-4 q), with the first 5 kA test, it ignited and melted along a test electrode contact, as it can be seen in Figure 4-4 q, avoiding further testing and thus no data results can be provided.

The current and voltage signatures of the first and the last LIC applied to one of the samples of each of the four studied fabrics are shown in the upper part of Figure 4-4, beside each picture. Figure 4-4 b, e, and h correspond to the first impulse; Figure 4-4 c, f, and i, to the last impulse. Figure 4-4 k is the applied current signal to the F4-3 sample (i.e. the sample 3 of fabric 4) while Figure 4-4 l is the voltage drop across it, shown inverted due to the measurement system connection. After applying the LICs on each test sample, some patterns appeared on the fabric surface, particularly close to the electrodes as shown in Figure 4-4 a, d, g, and j. Horizontal patterns perpendicular to the current direction can be noticed in these pictures, the latter indicated by yellow arrows.

For all fabric samples of each type, the first cycle peak current value and its corresponding voltage datum of each LIC test were plotted giving a current-voltage (I-V) characteristic as shown in Figure 4-5 a to d. These characteristics correspond to the “dynamical” response of the material to the crossing current.

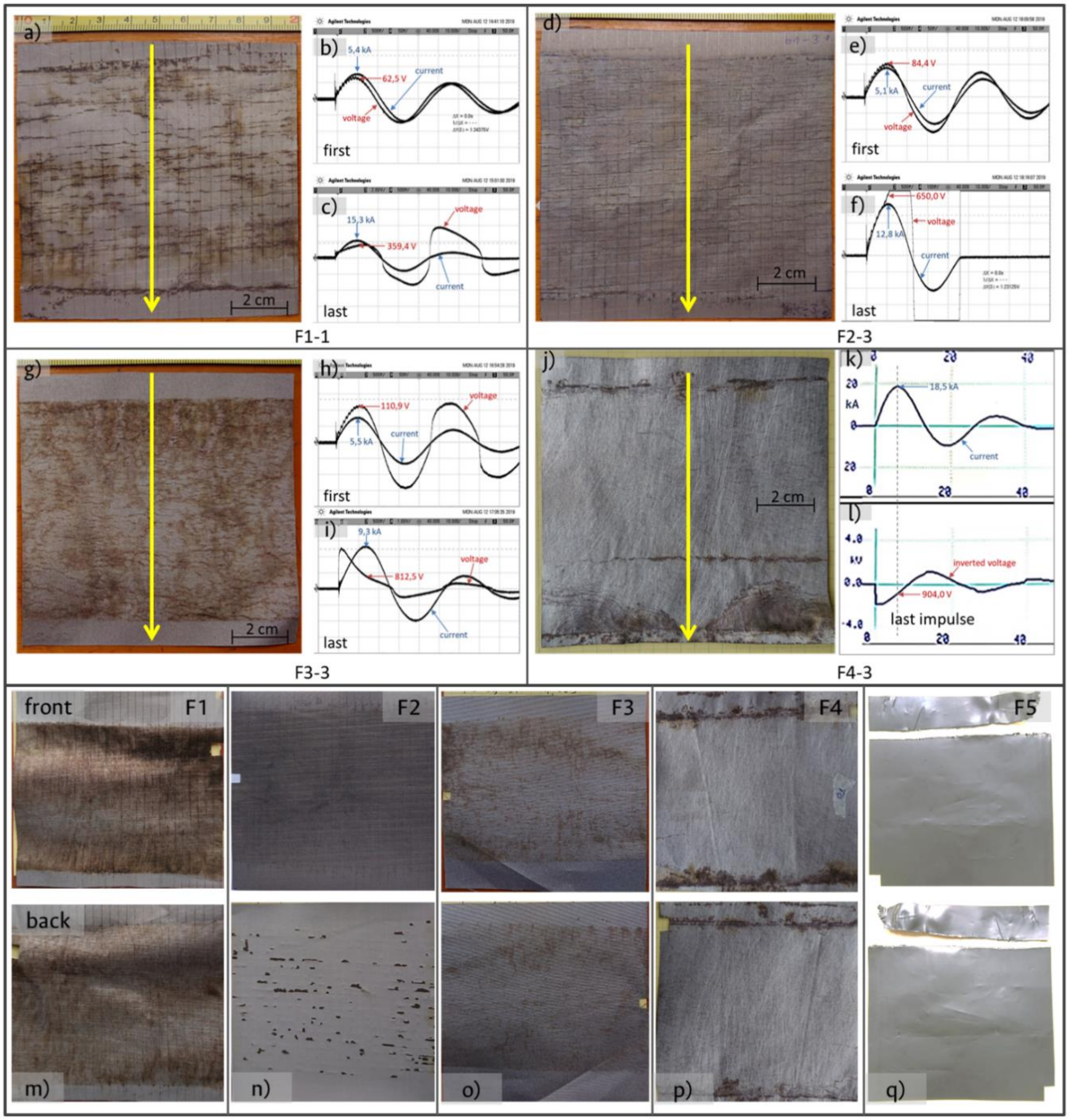


Figure 4-4. Photographs of tested electroconductive fabric samples showing some current and voltage signals. Images of rip-stop F1-1 (a), rip-stop with flame retardant (d), plain-weave (g) and nonwoven (j) conductive fabric samples after lightning impulse current (LIC) indicating the direction of the current flow with yellow arrows. Next to them are both current and voltage signatures of the first and the last impulse as follows: plots (b), (e), and (h) correspond to the first applied impulses, while (c), (f), and (i) to the last ones. For the nonwoven fabric sample F4-3, the current (k) and voltage (l) signatures are shown separately, the latter with negative polarity by the acquisition system connection. After LIC tests, some marks particularly perpendicular to the current flow appear in the fabric sample surfaces. In addition, both sides of each tested electroconductive fabric samples F1 (m), F2 (n), F3 (o), F4 (p) and the polymeric film sample F5 (q) are shown after the last applied impulse. The fabrics (samples F1 to F4) show marks in the front and back surfaces and the film (sample F5) shows the cut caused by the melting of the electroconductive surface. Note the flame-retardant composite in the back surface of the F2 (n) with a scratch pattern that is perpendicular to the direction of the current (vertical for all pictures).

For the first three impulses of all the current-voltage plots presented in Figure 4-5, an almost linear behavior is noticed, which indicates a constant electric resistance value for those levels of the current. Therefore, the "dynamical resistance" of the ECFs for the first impulses was calculated using the I-V data, as it is shown in the plots of Figure 4-4(b, e, h and k), as well as Ohm's law. The average resistance values obtained for the fabrics in ascending order are: 15 mΩ for F1, 19 mΩ for F2, 30 mΩ for F4, and 57 mΩ for F3.

The application of the fourth LIC produced a considerable variation in the electrical behavior on all tested ECF, particularly for the F3 plain-weave fabric. The most evident change observed in the sample F3-2 shows an erratic behavior compared with the other three samples. On the other hand, for the F4 fabric, the last applied LIC of 19 kA, produced changes of about 33 % and up to 96 %. This large variation was not expected from the projections of the previously three measured values of the fabric electrical resistance.

Energy estimation. The energy applied by the first positive semi-cycle of each LIC was estimated using equations (2) and (3). The average resistance obtained from the first three LICs of Table 4-3 is considered as the fabric resistance. The energy in joules related to the applied current in kiloamperes on each weave pattern is plotted in Figure 4-5 e.

Table 4-3. Average resistance in mΩ for the first three lightning current impulses of each fabric sample, average for fabric type, and uncertainty for 95 % of confidence for each weave type.

Sample	F1-1	F1-2	F1-3	F2-1	F2-2	F2-3	F3-1	F3-2	F3-3	F4-1	F4-2	F4-3
Resistance [mΩ]	15	15	16	15	17	24	56	47	68	29	28	34
$R_{average}$ [mΩ]		15			19			57			30	
uncert. [mΩ]		1			5			12			4	

After the second applied LIC, a progressive slight change in the color of the fabrics was noticed. From the original silver color, the surface acquires a soft dark tone after each impulse. This suggests overheating of the material probably due to the joule heating effect produced by the application of high LICs, which could even sublimate the thin conductive metallic layers when the current density surpass a critical value. LICs applied with enough high amplitude can produce loss of conductive material layer in some areas changing the fabric structure. This phenomenon increases the ECF electrical resistance and therefore the dissipated energy in the conductive material when a successive impulse is applied. In a previous work, the critical LIC amplitude for the sublimation and break-down of a dog-tag metallic chain (i.e. pearl-like necklace) was estimated in 17.4 kA peak for a 8/20 μs waveform [119]. For the tested fabric samples, the higher the lightning current impulse amplitude, the more the effect on the fabric surface was observed.

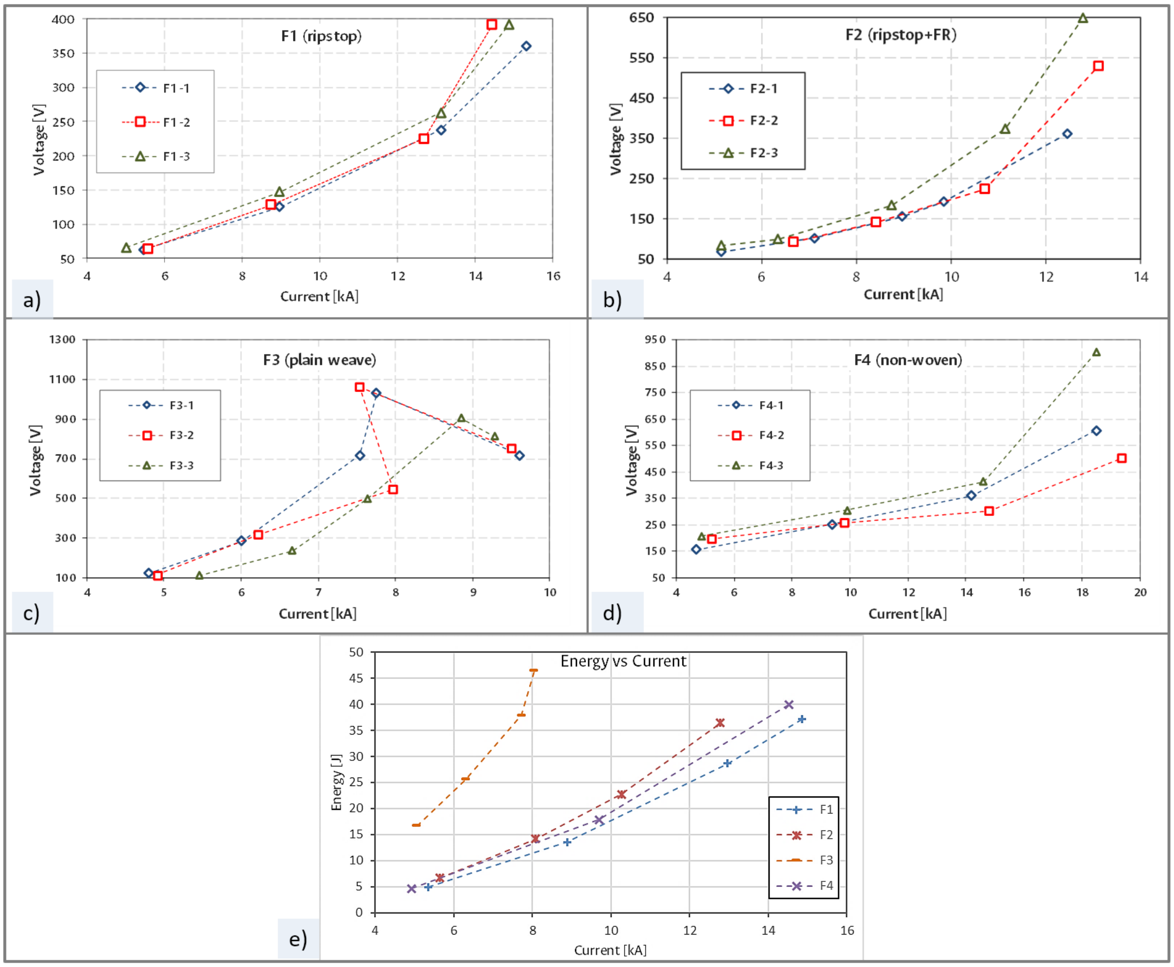


Figure 4-5. Voltage-Current graphs of the LIC tests on the electroconductive fabrics F1 to F4 (a to d) and Energy-Current averages plot of the subsequent LICs tests over the fabrics (e). Three samples of each fabric were tested with four subsequent increasing LICs for samples F1 (a), F2 (b) and F4 (d), and five impulses for sample F3 (c), where the sequence tests are represented by the colored lines (blue ◊, red □, green △), one for each sample. Note that horizontal and vertical scales are different in all graphs.

The Energy vs Current characteristic (Figure 4-5 e) shows an evident difference for the plain-weave F3. This plot reveals a similar behavior for the fabrics F1, F2 and F4, and that the plain-weave electroconductive fabric F3 dissipates more energy, even at lower current values. This is consistent with their electrical resistance presented in Table 4-3, where for F3 it presents the highest value of the four fabrics evaluated. Figure 4-5 also shows a clear particular behavior for F3 (Figure 4-5 c) after the third LIC, indicating a strong change in its electrical resistance and conduction mechanism.

SEM observations. To assess the morphology changes on the OUT fabrics after the LICs, some selected samples were observed by means of the Scanning Electronic Microscope (SEM). The magnification was increased over some scratches on the surface as shown in Figure 4-6.

The secondary electron image detection (SEI) of the SEM microscopy (Figure 4-6 m and 5 n) allows easy identification of the conductive and non-conductive materials, mainly because the atomic number of metal atoms are greater than those of isolating organic compounds. The dark areas of the non-conductive polymer filaments contrast strongly with the clear areas of the conductive metallic coating.

Under the conditions described, SEM micrographs show optically that the woven fabrics (samples F1, F2 and F3) would better support the high-currents flow than the nonwoven one (F4). F4 nonwoven fabric surface (Figure 4-6 j, 5 k, 5 l) has regions that endure worse the high-currents flow despite to their electrical response and visual aspect. This might suggest that the woven fabrics have a better performance to endure the current flow, i.e., the most ordered and straight the weave the more its capacity to drive impulsive currents. However, this observation could depend on the length, geometry, the material, and the production technique of the fibers in nonwoven fabrics. Furthermore, the F3 plain-weave with a pattern like that of the rip-stop fabrics F1 (Figure 4-6 a, 5 b, 5 c) and F2 (Figure 4-6 d, 5 e, 5 f) but with a loose weave, shows a greater resistance and consequently greater energy dissipation. Although further research on knitting fabrics, this work does not address this weave type, as it has a more intricate weave pattern that changes the yarn paths. Therefore, lower performance would be expected.

Using the SEM Energy Dispersive Spectrometry analysis (EDS), the elemental composition of the conductive surface layer was estimated over a sample of F1 rip-stop fabric. The EDS semi-qualitative chemical analysis identified a composition of 55%Cu – 45%Ni on a non-affected spot area of the fabric surface, as shown in Figure 4-6 m. Similarly, on the observation region of the surface of the sample F1 after lightning current tests, it was identified an elemental composition of 44% Cu–36 %Ni–16 %O–4 %C, as shown in Figure 4-6 n, where carbon and oxygen are two basic elements of the inner polyester filaments.

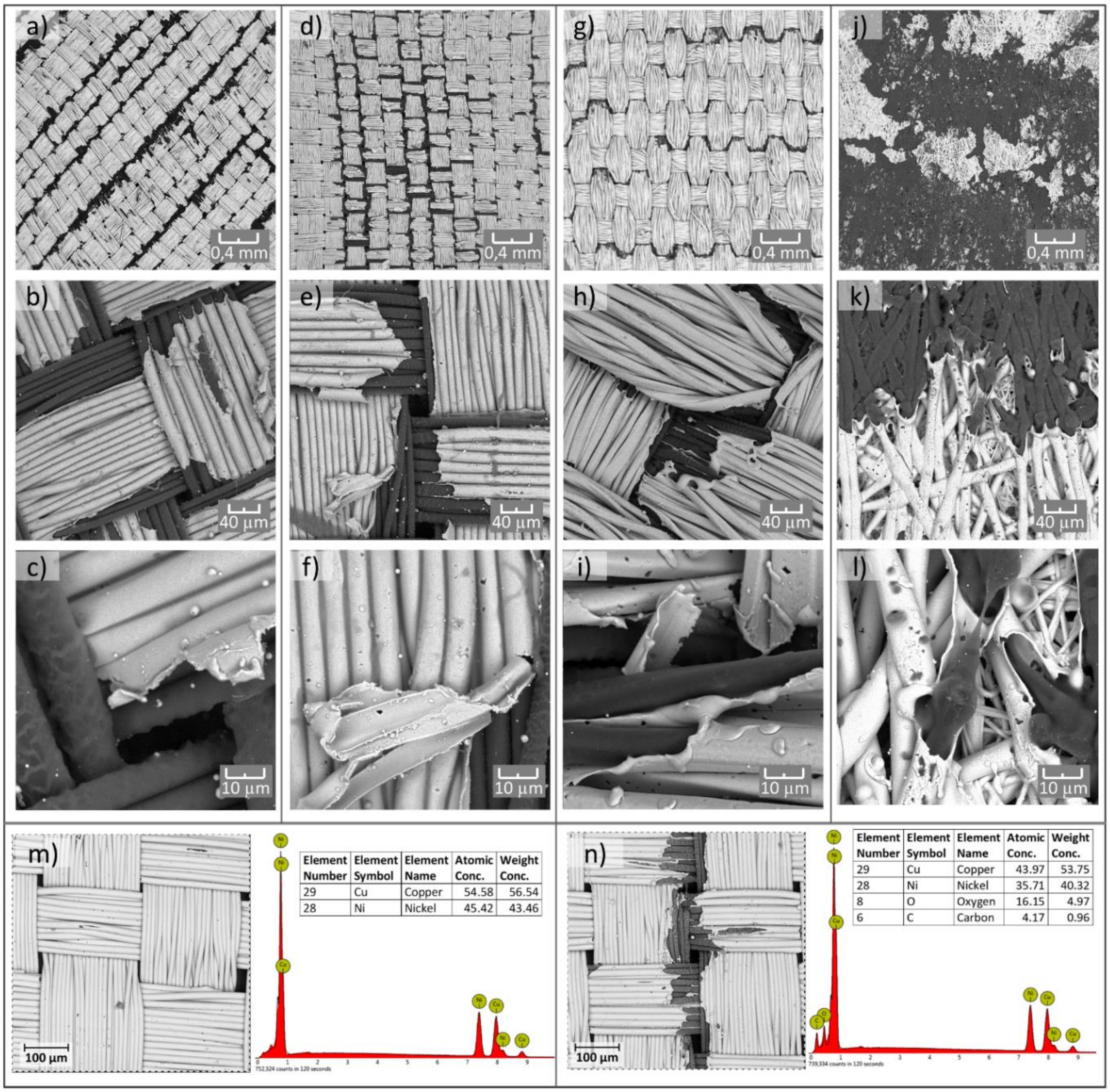


Figure 4-6. SEM micrographs and SEM-EDS chemical elemental composition. The SEM micrographs (at HV 20.0 kV) of the four fabric samples after the lightning impulse tests show the change in the conductive surface of the four tested types: a), b) and c) rip-stop F1; d), e) and f) rip-stop with a side coated with a flame-retardant F2; g), h), and i) plain-weave F3; j), k), and l) nonwoven type F4; and SEM-EDSs show semi-qualitative chemical elemental composition analyses before (m) and after (n) lightning tests on a sample of the rip-stop fabric F1.

The resistance value of the electroconductive fabric is a key parameter of the ECF intended to drive lightning currents. The elemental composition of the yarns conductive layer defines the resistivity, therefore the resistance. According to the SEM-EDS analysis (Figure 4-6), the tested fabrics in this research are made from yarns with a conductive layer of copper-nickel alloys in a concentration of approximately 55 % Cu and 45 % Ni. Bundling many yarns from materials with enough low resistivity can lead to weaves with low resistance able to withstand lightning currents.

Carbon fibers, carbon nanotubes CNT, graphene-coatings, and other non-metallic conductive materials based on organic compounds have relatively high resistivities compared with metallic ones, such a copper, leading to high resistance values and therefore, high energy dissipation in form of heat. The polymeric carbon-coated film F5, shows that it cannot withstand even a single 5 kA LIC, because the heat generated melt the material itself along one of the contact electrodes.

Loss of material and "crosswise asperities". Table 4-4 shows the weights average taken for the three fabric samples before and after tests, revealing an average loss of approximately 0.8 % for F1 (ripstop), 23.2 % for F2 (ripstop + flame retardant), 0.4 % for F3 (plain weave), and 0.7 % for F4 (nonwoven). Because of the melting and sublimation of the outer metallic layer of the yarns, the conductive material is lost in some regions of the fabric surface. In this case the polyester base material of the filament core is exposed and can be recognized as some dark patterns presented in previous figures. This loss of material results in mass loss.

Table 4-4. Mass loss in 10 cm x 10 cm electroconductive fabric samples before and after tests

	Before		After		Difference	%
Sample	[mg]	Std. Dev.	[mg]	Std. Dev.	[mg]	
F1-Avg	828.3 ± 0.3	4.4	822.1 ± 0.3	6.2	6.2 ± 0.6	0.8
F2-Avg	2389.4 ± 0.2	52.1	1836.1 ± 0.5	137.0	553.3 ± 0.7	23.2
F3-Avg	1204.6 ± 0.1	6.8	1199.4 ± 0.6	7.0	5.2 ± 0.7	0.4
F4-Avg	791.9 ± 0.5	29.8	786.1 ± 0.2	30.1	5.8 ± 0.7	0.7

In particular, the F2 samples show the greatest loss, also due to the release of small pieces of the flame-retardant layer composite, following the pattern of scratches left on the ECF surface as shown in Figure 4-4 n. The final damage of the flame-retardant coating composite on the back side, and the surface marks on F2, suggest that this composite help to increase the physical strength of the fabric against lightning current damage, possibly due to the increased capacity of the coating to support higher temperatures. However, the composite layer could increase the electrical resistance compared with sample F1, as shown in Figure 4-5 and Table 4-3, because it decreases the heat release capacity of one side of the fabric. Additionally, the composite layer increases the stiffness, mass, and thickness of the ECF, hindering its manageability.

As shown through micrographs of Figure 4-2 and Figure 4-6, the metal layer on the yarn of the fabric forms a net of tubes that can conduct LICs. This conductive network may gradually be lost by melting due to the intense currents. Despite this, the fabric continues conducting subsequent lightning impulse currents through the remaining paths but losing more of the metal coating, in some cases until the non-conductive inner polyester core is exposed as shown in Figure 4-6. The SEM micrograph of Figure 4-6 l even reveals molten polyester of the core outside the little tubes formed by the conductive sheath of the nonwoven fabric. The mass change, which resulted from the melting and loss of material after lightning tests, presented in Table 4-4, does not suggest any relation with the capacity of the electroconductive fabric to withstand the laboratory lightning currents. The F2 rip-stop fabric with flame-retardant layer had the greatest mass loss (23.2 %), while the F3 plain-weave, which had the worst electric result, had the lowest loss (0.4 %). This result may be more related to the mechanical effect and would only indicate the loss of material ejected in the air. It does not necessarily mean that the lost material left the weave, as it could remain tangled up in the fabric yarns, as Figure 4-6 (c, e, f, i, and l) shows.

The metallic outer layer of the yarns was overheated by the Joule effect, causing horizontal scratches that were perpendicular to the current flow. Even though the exact mechanism of how horizontal marks are produced is not totally clear, but it is possible to give an explanation by thinking the electroconductive tested fabrics as networks of conductive tubes. When a lengthwise current flows through a single tube, and this tube experiences a change in direction, the current density inside increases or decreases according to the change to which it is subjected, analogous to a pipe that transports liquids. Where the current density increases, the heating increases because of the Joule effect and, conversely, when the current density decreases, the heating decreases. As the fabric has a regular symmetrical array, the pattern of scratches appears crosswise to the current flow. This agrees with the observation of the previous paragraph that relates ordered and straight weaves with increased capacity to drive impulsive currents. According to this, it is possible that a perfectly smooth, plain and straight nonwoven fabric (similar to F4) with most long fibers oriented lengthwise to the current flow could withstand higher electric currents despite their fragility. Therefore, both the weave pattern and the fabric structure have an important effect on their response against LICs.

Considering the fabric as a simple homogeneous conductive surface, the loss of material, due to the conduction of a high lightning current, leaves some scratches or “crosswise asperities” that constrain the conduction of the electrical current to certain remaining paths, in similar way to the interface between two bulk electrical contacts. Figure 4-7 shows a sequence representation of the crosswise asperities on the conductive fabric surface. The remaining “contact paths” after the LIC test can provide the conducting routes for the electrical current flow of subsequent discharges, as lightning flashes could have more than a single stroke [167].

Crosswise asperities produced after tests on the conductive surface of the fabrics maintain the ability to conduct electrical currents but increase the resistance of the material, as shown in Figure 4-5 for the four fabric types, where its resistance value has a considerable change after the third lightning impulse current. For these fabrics, ohmic behavior can be considered until the third LIC whose current value depends on the fabric itself.

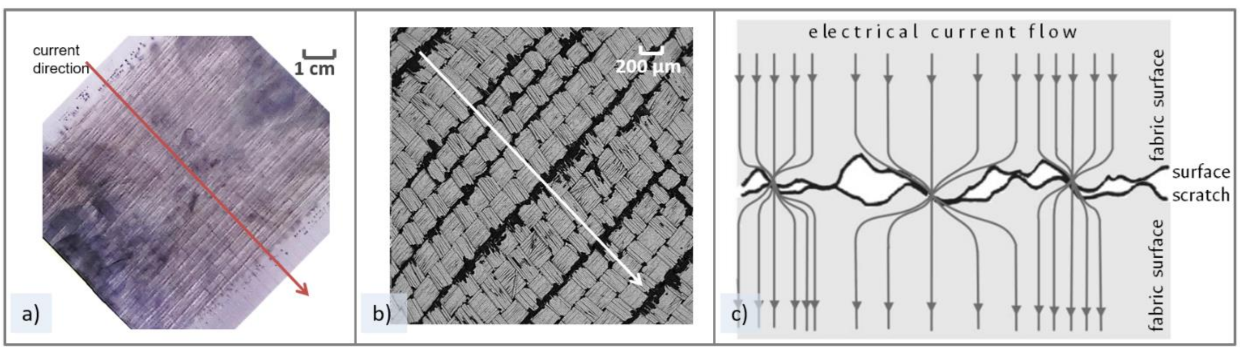


Figure 4-7. The lightning impulse currents (LICs) produce a scratch pattern on the fabric surface (a) perpendicular to the current direction, easy visible in the SEM image (b). The scratches left on the conductive fabric surface after LIC tests, can be considered as crosswise asperities as shown in the free interpretation of the formed contact interface (c).

However, the sample F3-2 (sample 2 of the fabric F3 – plain-weave) shows a strong variation after the 8 kA impulse, reducing the current value but increasing the voltage. At 8 kA gives a resistance of 69 mΩ and for the next peak value of 7.5 kA gives a resistance of 141 mΩ. A higher current value was expected at this point, but the output current of the generator setup is determined by the impedance of the fabric. This unexpected point in the F3-2 response shows that the F3 fabric has a critical value of current conduction since it also occurred for F3-1 and F3-3 despite the little shift of their response.

For subsequent discharges, the scratch is in itself an interface between neighbor conductive areas with discontinuities or gaps that determines the paths that can effectively conduct subsequent currents. As it is represented in Figure 4-7c, the remaining conductive paths continue driving currents, while open ways and gaps cannot do it. However, in absence of these remaining conductive paths and with enough high electric field, the air dielectric strength of the gap distance between conductive meeting areas breaks down, conducting the currents through the surface. The dielectric strength of air depends on the shape and size of the electrodes, temperature, pressure, and moisture of the air. Under homogeneous conditions, at atmospheric pressure, and in accordance to Paschen's law for air, the breakdown voltage of a 10 µm gap is less than approximately 350 V (i.e. 35 V/µm) [168].

These changes suggest that there is more than one conduction mechanism in the ECF.

Conduction mechanisms and LIC endurance of the tested electroconductive fabrics. The obvious conduction mechanism is the flow of current through the material of the conductive surface itself, as inferred for the first three impulses. For subsequent discharges above the third, the scratches become interfaces between neighbor conductive areas, with gaps and bridges, determining the paths that could effectively conduct new currents. The remaining conductive paths continue to carry new currents. On the other hand, in absence of conductive paths in the crosswise asperities, the electric field can be high enough at the open meeting areas or gaps, breaking down the air strength and producing small discharges (sparks) that bridge the gaps, enabling the conduction of successive lightning currents through the electrical discontinuities.

For fabrics F1, F2 and F4, the resistance behavior displayed in the Current-Voltage characteristics of Figure 4-5, extends to higher current values suggesting that, at least electrically, these fabrics support better LICs than F3. Despite more measurements are needed, the first three impulses tests for all tested fabrics show an approximately linear ohmic resistance behavior (as the voltage follows the current signal and the plots I-V show a somewhat linear trend), after which the yarns change their structure enough to modify permanently the weave, implying an alteration in the electrical current conduction mechanism in a similar way to mentioned previously. From the outcomes of our experimental tests, there is not enough evidence to conclude that subsequent LICs below a critical peak value can produce progressive damage in the fabrics. Conversely, it can be said that after the third current impulse, suggested as a critical value, the scratches are more marked and the damage is progressive, as each time fewer and fewer conductive paths remain.

Woven type textiles comprise weave patterns according to its final use. The samples of the four tested weaves show a tendency to begin to burn up more easily crosswise, perpendicular to the current flow, and left on the surface fabric a pattern of horizontal scratches. In the nonwoven fabric F4, as shown in Figure 4-4 and Figure 4-6, the horizontal melting effect is marked not only as lines but also as large areas following a perpendicular pattern.

The rip-stop fabric has a special weave array with a reinforcing technique that makes them mechanically resistant to ripping and tearing. Conversely, the tested nonwoven fabric appears more fragile with a paper-like brittle feature. Despite the similar energy-current and voltage-current characteristics against lightning impulses between F1 and F4, fragility is an undesirable attribute.

Considering only the visible and electrical effects of the lightning currents on the tested fabrics and discarding the mechanical ones, the rip-stop weave has proven to be a tough material with better performance to support lightning impulse currents like those produced by electrical atmospheric discharges.

Furthermore, considering the lightning parameters given in Tables A.1 and A.3 of IEC62305-1 [19], the 50 % value of a typical first negative stroke corresponds to a current of 20 kA peak and it has a probability P=0.8. This suggests the possibility to conform lightweight and portable LPS with electroconductive fabrics according to the results of the LIC tests. Additionally, it is very important to remember that both direct and indirect lightning impulse currents from natural atmospheric discharges can cause injuries. In fact, a larger number of fatal accidents are caused by step potentials, despite their relatively low current intensities, but sufficient to produce cardiorespiratory arrest [169]. Further study is necessary on this subject to have more accurate information.

4.2.7 Conclusion

Four types of electroconductive fabrics and a carbon-impregnated polymeric film were tested in high-voltage laboratories to assess the effect of lightning currents on them. Lightning impulse currents (LIC) of 8/20 μs waveshape were generated and used in the laboratory to simulate natural lightning strikes. Consecutive LICs with increasing amplitudes greater than 5 kA, were applied to 10 cm squared samples of rip-stop, plain-weave, nonwoven electroconductive fabrics, and over a polymeric carbon impregnated film. The tested fabric samples withstood the trials with the progressive increasing currents up to 18 kA, but not the carbon impregnated film which could not withstand even the 5 kA current. For each fabric tested, a constant ohmic resistance behavior was observed since the voltage follows the applied current, up to a certain critical value of the applied LIC, after which the current-voltage characteristic changed. Therefore, two mechanisms of electrical conduction on the fabric surface are proposed here. The microscopy inspections reveal that the pattern of scratches left by the LICs on the fabric surfaces are due to the melting of the outer conductive layer of the fabric yarns. The outcomes suggested that from the four tested electroconductive fabrics, the rip-stop is the better weave type for potential application in lightweight and portable Lightning Protection Systems to mitigate lightning risks in outdoor applications such as tents and mobile shelters.

4.2.8 Acknowledgments

The authors would like to thank the “Universidad Nacional de Colombia” (UNAL) and its professors for all the help and support, access to the SEM and the use of the HV laboratories, Eng. Francisco Amortegui and Eng. Fernando Herrera of the LABE and the Electric and Electronic Department. We also thank Dr. Jorge Ignacio Villa of the Sciences Department of UNAL, to Andres Fernando Gil Plazas from the “Centro de Materiales y Ensayos of SENA Regional Distrito Capital” for the SEM technical support, and to Diana Marcela Forero for her help in the review of the text. We also want to express our gratitude to Zhejiang Saintyear Electronic Technologies Co., Ltd. for the generous samples of conductive fabrics provided for our research.

4.3 Behavior of an electroconductive rip-stop fabric under 8/20 µs lightning current [3, 4]

Lightning strokes can hit buildings, structures, living beings, and the ground, jeopardizing the integrity and health of people and animals and causing damages to trees and equipment. Some outdoor human activities in backcountry places require adequate lightning protection systems (LPS) to reduce the risk of damage to health. Preliminary research has shown that the use of electroconductive fabrics could serve as part of lightweight LPSs. In this research work we investigate the behavior of samples of a rip-stop electroconductive fabric submitted to lightning impulse currents with amplitudes in the range 5 kA to 20 kA and 8/20 µs waveshape. Both the voltage and current signatures were recorded. The results show that there is more than one mechanism of electric conduction in the electroconductive fabric, allowing it to endure lightning currents.

4.3.1 Introduction

The lightning strikes, related to the electric atmospheric activity, can cause serious traumas in people and living beings as also severe damage in buildings, structures, and equipment. Some human group activities are more vulnerable to lightning traumata, mostly those related to outdoor activities or placed in open fields [152], [153], [170]. Some places on the planet experiment more lightning activity than others and several locations are more prone to cause injuries due to the very high lightning activity. The 100 hotspots places of the world have densities between 83.45 and 232.52 flashes·km^{-2}·a^{-1} [1]. There are many reports in the technical literature and in the media about those affected, injured, or killed by lightning, even with multiple human and animal casualties.

When lightning strikes directly to earth or to a tall structure, hazardous currents can flow from the strike point through the ground to an individual or living being. This coupling mechanism between lightning and living beings, known as ground current, earth potential rise or step potential, accounts for about 50 % to 55 % of all injury cases [169].

[3] Authors: Jorge A. Cristancho, Jorge E. Rodriguez, Carlos Rivera, Francisco Roman, Alexandre Piantini, Miltom Shigihara, Clóvis Y. Kodaira.

[4] The paper entitled as “Behavior of an Electroconductive Rip-stop Fabric under 8/20 µs Lightning Current: Preliminary Results” was presented at 35th International conference on lightning protection ICLP and XVI International Symposium on Lightning Protection SIPDA (ICLP-SIPDA 2021)

In some previously laboratory work reported [30], [147], [170], it has been shown that some electroconductive fabrics can drive laboratory lightning currents and could conduct those produced by natural lightning, particularly the indirect lightning currents that flow through the ground due to the strike.

This paper shows the results of observations and laboratory outcomes of lightning impulsive current (LIC) tests carried out with an impulse current generator of 8/20 µs waveform and output peak currents from 5 kA to 20 kA over several untested samples of an electroconductive rip-stop fabric.

4.3.2 Electroconductive rip-stop fabric

Electroconductive fabrics are made with fibers, yarns or threads made from conductive, low conductive, or non-conductive substrates coated or embedded with electrically conductive elements such as nickel, copper or silver. Depending on the application other metallic materials or alloys, such as gold, steel or titanium, are used, as well as non-metallic ones (e.g. conductive polymers, carbonaceous, or graphene) [156], [157]. Figure 4-8 shows a typical structure of an electroconductive single fiber and a micrograph of a woven rip-stop conductive fabric. Each warp or weft yarn has several individual fibers.

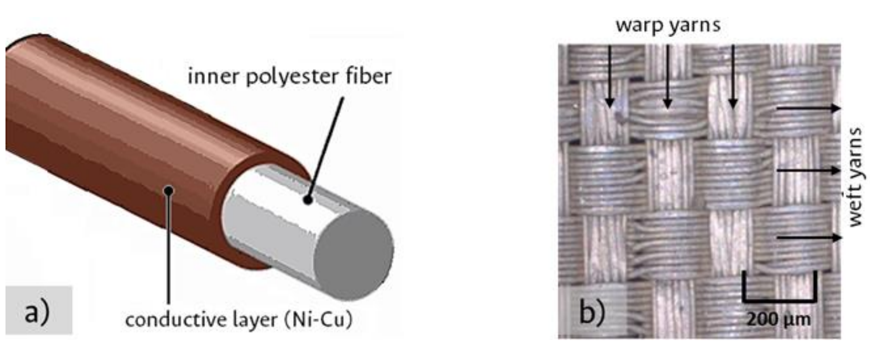


Figure 4-8. Structure of an electroconductive fiber (a) and a micrograph of a conductive fabric indicating the warp and weft yarns (b).

Each yarn of the rip-stop fabric has several fibers, each one with a core of an insulating material coated with an outer conductive layer (in this case, inner polyester with an outer metal alloy layer). Since these fibers can be fabricated by a simple metal-deposition treatment, the fabrics made from them constitute one of the most popular products in the electroconductive fabrics market [171].

There are several types of conductive fabrics depending on its weaving, fiber materials, layers, plies, threads, yarns, thickness, and weight, among other parameters. Rip-stop fabrics are woven textiles with its yarns interlaced in mutually perpendicular directions, as showed in Figure 4-8 b, interweaving warp-and-weft yarns in a pattern that prevent the fabric rip. Non-woven fabrics are textiles whose random structure is produced by the bonding or interlocking of fibers. In this work the tests were performed on a rip-stop fabric made from warp and weft yarns of 48 fibers of 15 µm diameter and an average conductive layer of 1 µm thickness.

It is important to keep in mind that a specification parameter of the conductive films and fabrics is the “sheet resistance” expressed commonly in ohms per square units (Ω/□). In our case, this mean that the ohmic resistance value is given for a surface square of the fabric independent of the side length [30], [147].

4.3.3 Setup and methodology

A Lightning Impulse Current Generator (LICG) of the Lightning Laboratory of the Institute of Energy and Environment of the University of São Paulo (IEE/USP) was used to assess the endurance of the electroconductive ripstop fabric against lightning currents.

The fabric samples were trimmed of a commercial electroconductive fabric roll. Cuttings of 10 cm x 10 cm indicating the warp direction of each sample were done to maintain the orientation condition in all tested sections. The main characteristics of the electroconductive ripstop fabric given by the manufacturer are: weight 90 $g \cdot m^{-2}$; thickness 0.1 mm; sheet resistance ≤ 0.05 (Ω/□); conductive material nickel-copper alloy; core material polyester. The elemental composition of the conductive layer is about 43 % Ni and 57 % Cu [11].

The LICG was adjusted to generate standard 8/20 µs impulse current waveshapes with amplitudes of 5 kA, 10 kA, 15 kA and 20 kA. The schematic circuit of the LICG is shown in Figure 4-9. 8/20 µs was selected as it is a standard waveform from IEC 60060-1:2010 and due to availability in the laboratory.

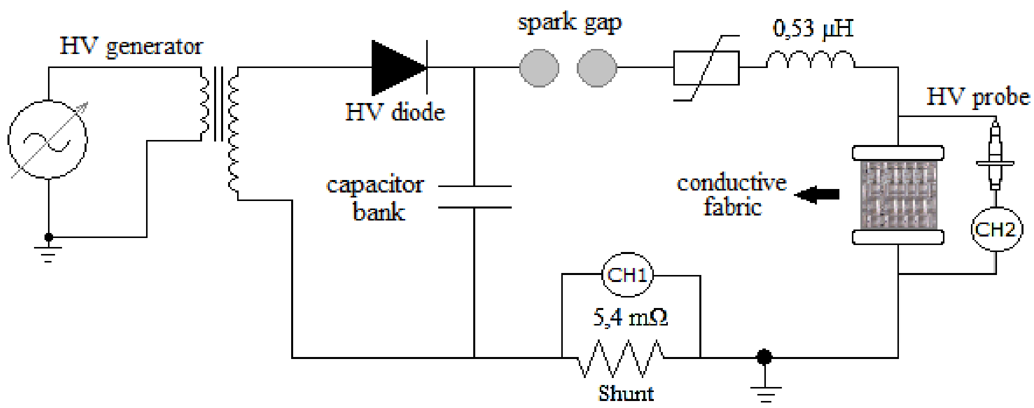


Figure 4-9. Setup of the 8/20 µs Lightning Impulse Current Generator used for testing the electroconductive rip-stop fabrics.

Current and voltage signals were measured over the fabric during the test and recorded to postprocess work through a two-channel digital acquisition system with 4 ns step and 40 µs record length. Figure 4-10 shows the control system console and the digitalization measurement unit used for the tests. Aluminum electrodes were used to give support and electrical contact between the current generator and the fabric sample.

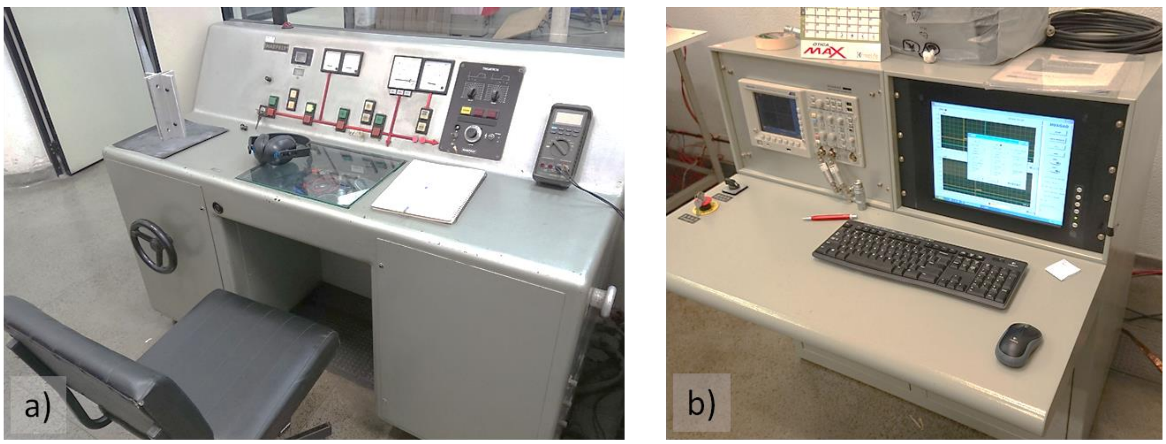


Figure 4-10. Control panel console (a) and Digital Acquisition System (b) of a LICG at the IEE/USP High Currents Laboratory.

The methodology used was similar to that described in [30], [148] as follows: four sets of three samples of electroconductive ripstop fabric of 10 cm x 10 cm, with warp orientation identified and all placed in the same way in the test setup were subjected to 8/20 µs Lightning Impulse Currents (LIC). Each sample of the set was exposed to a single impulse current with peaks of 5 kA, 10 kA, 15 kA and 20 kA. Pictures of both sides of the fabric surfaces were taken for visually comparisons before and after the tests. Figure 4-11 shows the fabric placed in the electrode clamps of the LICG setup before and after the 15 kA test. Notice that each single sample was subjected to a single LIC. At the end of the experimental procedure, four sets of three samples tested with the same peak current value, for a total number of twelve tested samples, were analyzed. The digitalized measurements were recorded and postprocessed in a spreadsheet in order to obtain both voltage and current plots.

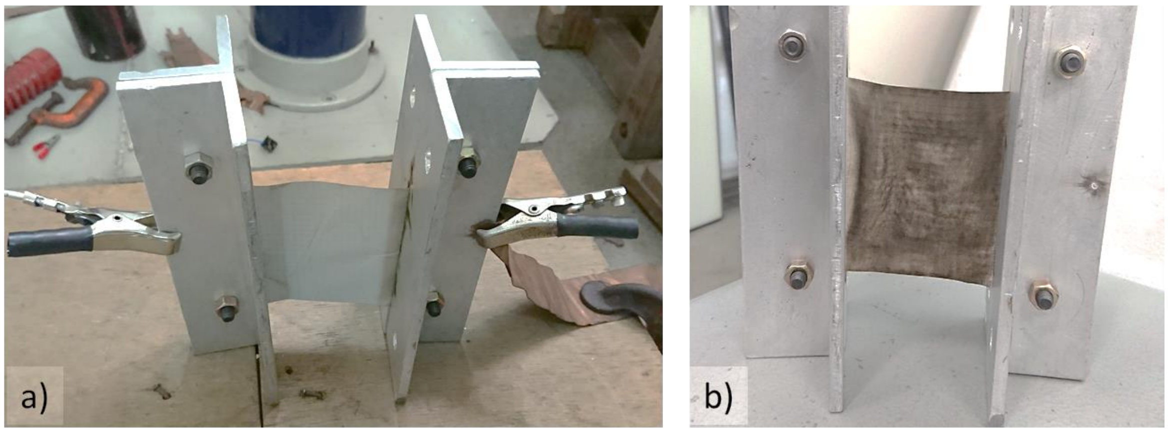


Figure 4-11. Electroconductive ripstop sample placed with the aluminum clamps before (a) and after (b) the 15 kA, 8/20 µs lightning impulse current test.

4.3.4 Results

After the tests procedure not evident surface changes were observed at the 5 kA fabric tested samples, while the ones tested with the highest impulse current values experienced a visual change on their surface. Figure 4-12 shows some selected electroconductive fabric samples after the tests with different amplitudes of the 8/20 µs applied current waveshape. The superimposed yellow arrow indicates both amplitude and direction of the applied current impulses. The progressive affectation of the sample surface with the increasing peak amplitude of the applied lightning impulsive current can be noticed in the picture. For the 10 kA peak current, the formation of regular scratches, perpendicular to the current path, in this case in weft direction (horizontally) it is noticeable. The upper and lower parts of the samples remained intact after the test procedure, since in these parts the fabric was supported and made electric contact with the electrodes, as shown in Figure 4-11.

The four graphs of Figure 4-13 show the measured current and voltage across the tested ripstop samples for the four current levels: 5 kA, 10 kA, 15 kA or 20 kA. It is noticeable the ohmic behavior for 5 kA with voltage and current in phase, the unexpected change for

10 kA, and the similar characteristics for the 15 and 20 kA currents. The 5 kA current and voltage signals correspond to an ohmic value calculated of about 31 mΩ, less than the 50 mΩ value given by the manufacturer. For the 20 kA case, the voltage peak is leading the current peak in about 2.5 µs.

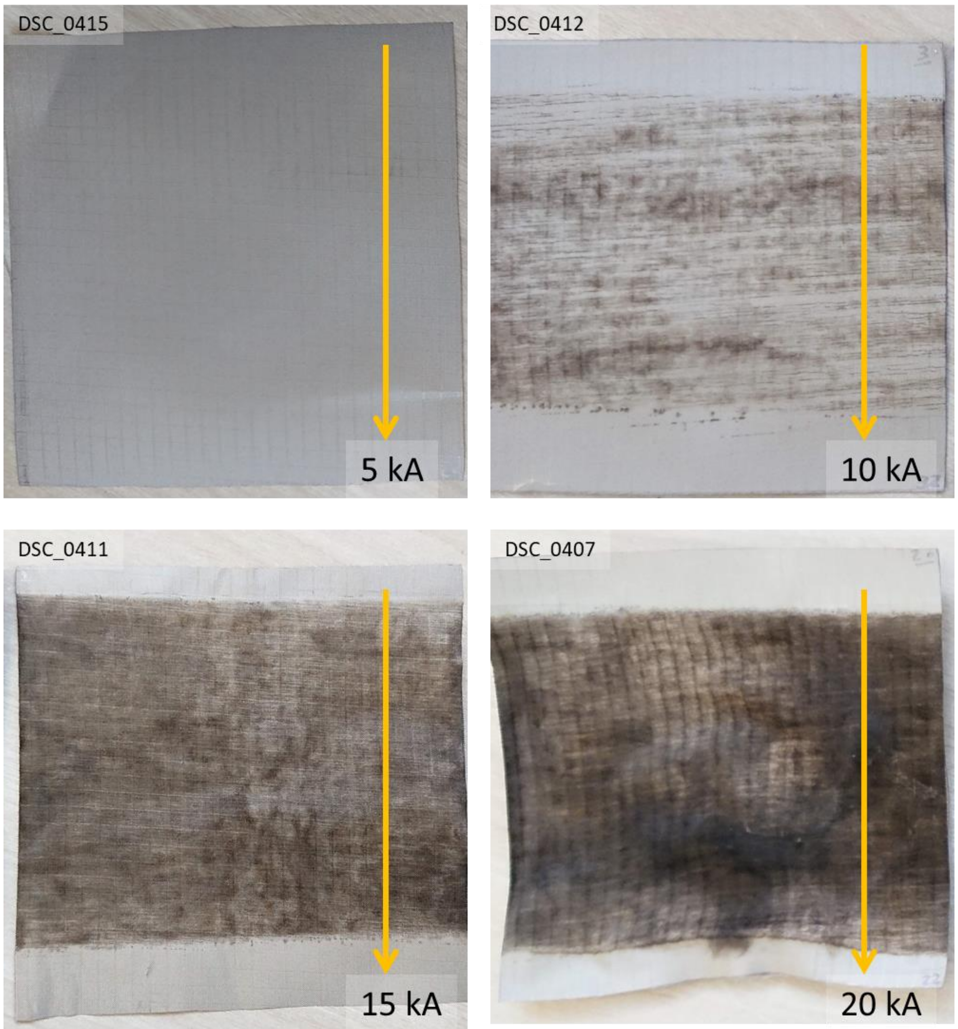


Figure 4-12. Four electroconductive ripstop samples after tested with 5, 10, 15, or 20 kA 8/20 µs lightning impulse currents. The superimposed yellow arrow indicates both amplitude and direction of the applied current impulse.

4.3.5 Discussion

In all the four current level tests, the current was able to flow across the electroconductive fabric, and the tested samples mechanically endured the test. The current signal shape shows that the generator (LICG) acted as a current source in all the experiments, maintaining the expected 8/20 µs impulse current waveshape. Based on the electric potential signal between the two electrodes at the fabric samples edges, for the 5 kA test the fabric showed an ohmic behavior, with the voltage following the applied current in a proportion of 31 mΩ determined by Ohm's law. The increase in the current value discloses that the fabric have a limit to this ohmic conduction, letting in evidence that there are at least two electric conduction phenomena as was suggested by the authors in [30], [148]. The change in the voltage shape, clearly observed in Figure 4-13 for the 10 kA current, is more evident considering that the other two samples assessed with the same LIC peak value (not shown in this paper) have an ohmic behavior, similar to the 5 kA tests. The sharp shapes of the voltage after 10 kA suggest a plasma conduction phenomenon likely due to a loss of conductive material from the surface.

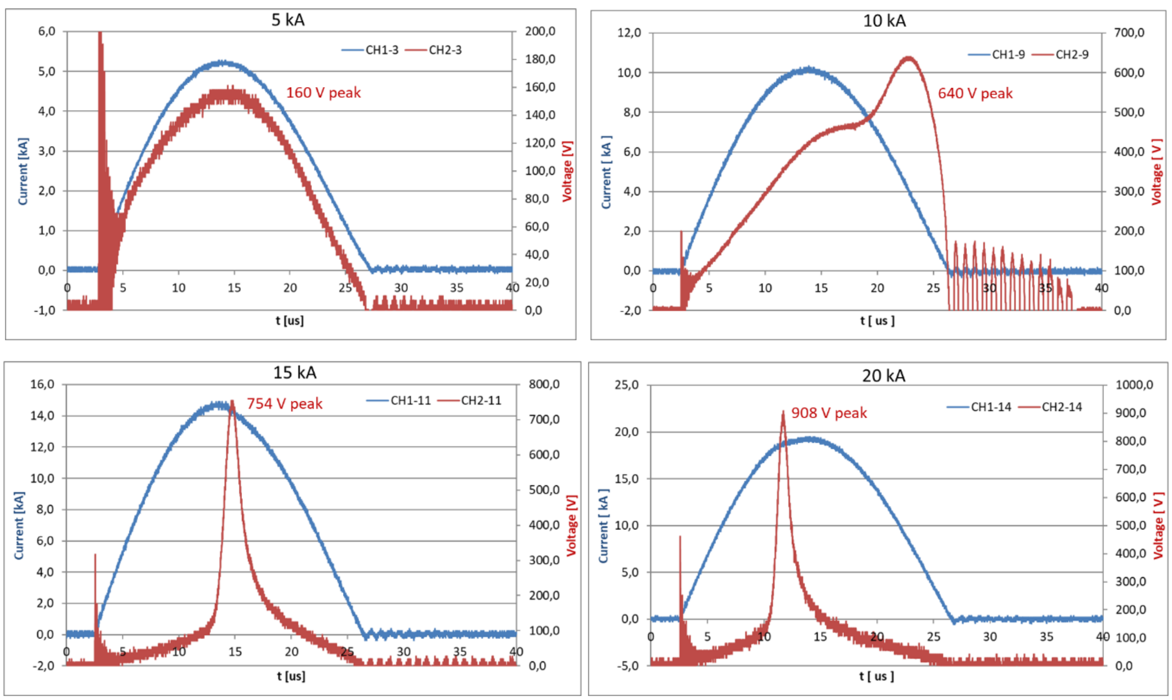


Figure 4-13. Current and Voltage signals for the four current level tests: 5 kA, 10 kA, 15 kA and 20 kA for different ripstop electroconductive fabric samples.

In this work, the perpendicular scratches observed in the fabric surface for the 10 kA test suggest that the weave pattern type have an strong influence on the current conduction, as it was previously observed [30], [148]. These scratches are burned marks formed by the overheat and sublimation of the conductive layer of the yarn fibers [148]. The larger currents have greater effect on the surface of the fabric, as shown in Figure 4-12. The increased damage of the conductive layer of the fibers may be due to the higher energy dissipation according to [148].

Additional work is being done for the use of high energy waveshapes over electroconductive fabrics, such as 10/350 μs standard waveshape, and some advances were presented in the ICLP-SIPDA 2021 congress. Further work includes resistance measurements and evaluation of the dynamic resistance under high current impulses before and after tests.

4.3.6 Conclusions

10 cm x 10 cm commercial electroconductive ripstop fabric samples were tested in the laboratory with 8/20 μs lightning impulse currents. At least two electrical conduction mechanisms were observed through the outcomes of the tested conductive fabrics. Ohmic conduction was evidenced up to 10 kA for the studied samples, while for higher currents a plasma conduction is more likely to occur. This research work shows that the tested ripstop weave pattern has a great potential to conform a personal lightning protection system as the samples endured tests with impulse currents with amplitudes up to 20 kA, thus reducing the risk to the health. The results suggest that the electroconductive ripstop fabric is capable to drive and divert lightning currents outside a living being, mainly those distributed flowing through the ground after a lightning strike to ground due to ground potential rise.

4.3.7 Acknowledgment

The authors are grateful to the *Universidad Nacional de Colombia* and the University of São Paulo by all the help and their International Exchange Program.

4.4 Personal protection against lightning using electroconductive fabrics [5], [6]

Protection against the effects of lightning with lightweight materials is a challenge for lightning researchers. We describe laboratory tests conducted on a proposed A-frame survival lightning shelter constructed from an electroconductive fabric. To estimate the stresses and injected energy that a human body would withstand when indirect lightning currents flow through the ground, a dummy inside the lightweight tent was also used. Voltage differences on the dummy between hand-to-hand, hands-to-knees, and head-to-feet for two basic positions were measured and recorded: in crawling position and lying down. The results show that when indirect lightning currents circulate through the ground, which are the cause of most fatalities, the energy on the dummy is less than 1 Joule, showing that this type of shelter strategy can help protect people's lives when they stay inside it.

4.4.1 Introduction

Exposure to lightning injury risk is determined by the lightning density of the site measured the number of cloud-to-ground lightning strikes per square kilometer per year (CG strikes km^{-2} a^{-1}), the population density and the availability of adequate shelters to protect against lightning [40]. 7 sites of the 10 most stormy sites in South America are present in Colombia, of which 3 are in the list of the 10 most stormy in the world [1]. This is one of the reasons why there are a large number of fatal injuries in the Colombian National Army due to lightning [172]. One of the most exposed population to the risk of lightning strikes are soldiers, who due to their service of duty, are forced to spend the night outdoors near trees and exposed places which are prone to receive direct and indirect lightning strikes [69], [118].

Among the main injury mechanisms caused by the coupling of lightning currents with human beings are: direct strike, contact potential, upward streamers, side flash and ground potential rise [3], [6], [38]. As Figure 4-14 a) shows, of these injury mechanisms, the one

[5] Authors: Jorge A. Cristancho, Jorge E. Rodriguez, Francisco Roman, and Andrés Mauricio Rojas G. that is with *Escuela de Logística* – ESLOG of *Ejército Nacional de Colombia,* Bogota D.C.

[6] This paper entitled as “Personal protection against lightning using electroconductive fabrics” was presented at 36th International conference on lightning protection ICLP 2022.

that accounts for the highest number of fatalities, in a developed country, corresponds to ground potential rise or ground currents with more than 50 % of the primary fatalities of all injury events reported as caused by lightning [38].

As is currently well known, in the ground current mechanism, injuries are produced by the flow of currents inside the body due to the earth potential rise produced by the main lightning currents diverted on the ground. When lightning strikes the ground, directly or indirectly (e.g., through a structure or a tree), in the vicinity of a person who is walking or standing, the voltage appearing between his two feet is also called step potential. Note in the schematic representation of Figure 4-14 b) that voltages U3 > U2 > U1, with the person lying down on the ground as the worst case.

For the development of a lightweight and portable lightning shelter, which can reduce the risk of lightning due to ground currents, several experiments were performed in the high-voltage laboratory. A lightning shelter is proposed, which was built and used in an experimental setup with a Lightning impulse current generator to simulate a lightning event scenario with a person inside the shelter. For this, an instrumented dummy was developed and used to measure the voltages and estimate the energies that would appear in a human body between hand-to-hand, hand-to-knee, and head-to-feet, in two common basic postures that would be taken inside the shelter: lying down and in crawling position supported by knees and hands.

Moreover, Comsol® Multiphysics software was used to simulate the lightning current flow and estimate some potentials to which a person would be subjected in the proposed shelter constructed with an electroconductive fabric. In the results and discussions, the measured voltage and estimated energy values in the instrumented dummy are analyzed, revealing the potential of the studied protection strategy for personal lightweight shelters against ground currents using electroconductive fabrics as a key element of the protection scheme.

4.4.2 Requirements for a lightweight lightning shelter

There are many situations in remote outdoor backcountry locations where is required a portable and lightweight personal protection systems against lightning hazards such as outdoor military and security operations, camping, and open-air sports [69]. Given the ground currents account for about 50 % of all lightning-caused human fatalities, it is reasonable to note that reducing the risk of this injury mechanism will reduce the overall risk of permanent lightning injury.

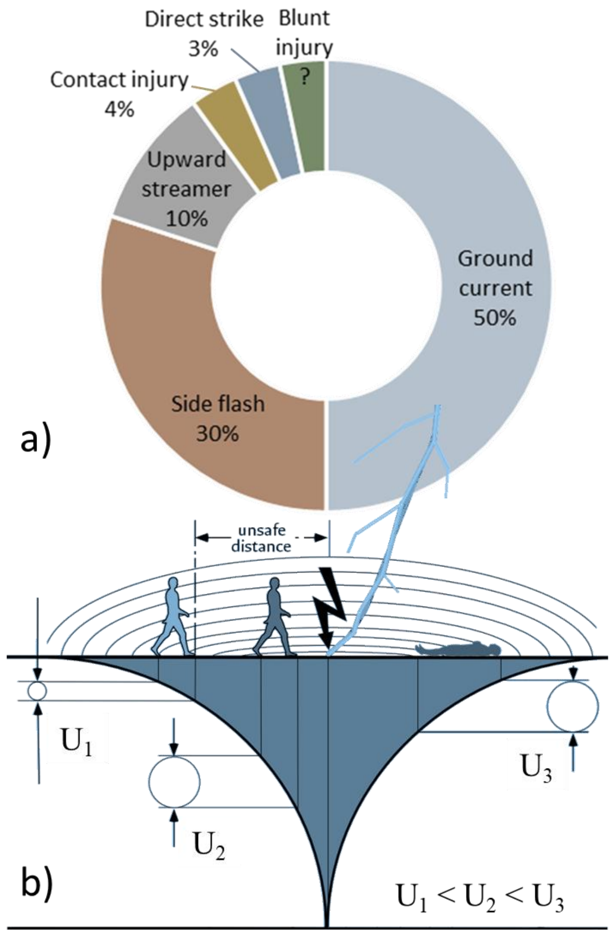


Figure 4-14. Lightning-caused fatalities by interaction mechanisms a) and ground potential rise schematic b). Source: a) adapted from [38] and b) from [173].

Any basic lightning protection system (LPS) includes air terminals, down conductors, and a ground system. Commonly, LPS are heavy and somewhat complex. A lightweight personal protection against lightning should include those elements, but should be lightweight and easy to install, as well as portable.

The earth potential rise by ground currents can be controlled by an equipotential surface. As has been shown in other works, electroconductive fabrics can endure high impulse currents that flow through the ground due to lightning strikes [25], [30], [147]. These electroconductive fabrics could be used in a shelter as an equipotential surface that can prevent dangerous lightning currents from entering the human body.

Preliminarily, the minimum requirements for a personal lightning protection that a person can transport easily in outdoor conditions would include: 1. Reduce the lightning risk, 2. Lightweight, 3. Portable, 4. Easy and quick to install, 5. Withstand environmental conditions such as sun, water, wind, and moisture, 6. Withstand basic mechanical use such as folding, tear resistance, and minor soil deformities. Standard ISO 5912 deal with some requirements for camping tents and test methods [174] that could be applied to this type of lightning shelters. On the other hand, the technical report IEC/TR 62713 “Safety procedures for reduction of risk outside a structure” introduces the lightning strike prevention and gives some precaution measures when this type of risks exists [25], [43] and should be taken into account combined to the use of a lightning shelter.

4.4.3 Electroconductive fabrics for shelter

Electroconductive fabrics (ECF) are textiles with the ability to conduct electrical currents by conductive materials in their constituent fibers and yarns. A commercial type of ECF made from Nickel-Copper alloy and polyester materials was used to construct an A-frame tent as a proposed survival lightning shelter. The ECF fabric has rip-stop characteristics to resist tearing. Figure 4-15 a) shows a micrograph of this fabric.

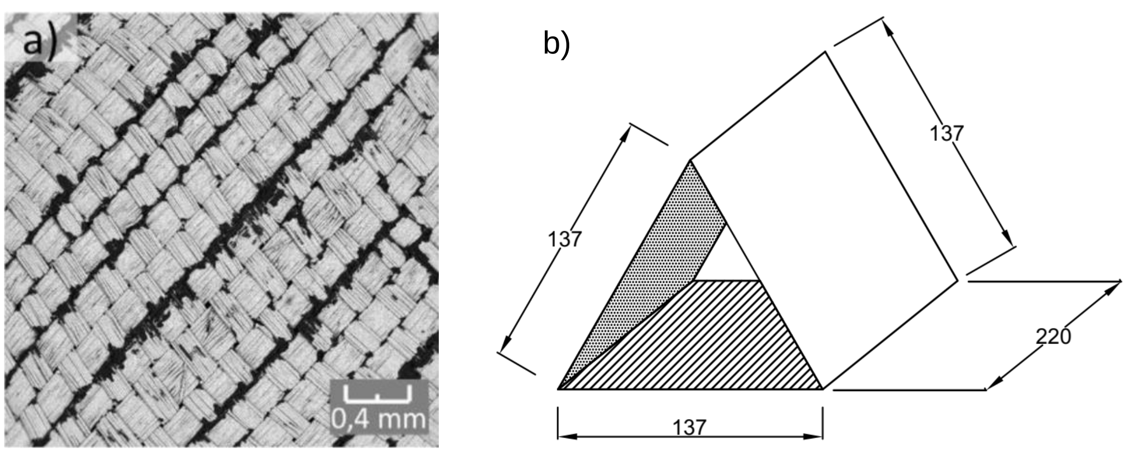


Figure 4-15. a) SEM micrograph (HV: 20.0 kV) of a rip-stop electroconductive fabric sample after (5, 9, 13, 15) kA lightning impulse tests, and b) outline of the proposed A-frame shelter with dimensions in cm. Source: a) [147].

The dimensions and shape of the proposed shelter follows the Colombian Army´s own standard, modeled as a basic tent with an A-frame shape (see Figure 4-15 b). This basic shape for one person makes it easy to install and use, lightweight and portable.

4.4.4 Experimental simulations tests

A lightning impulse current pulse generator (LICG), the proposed shelter, and an instrumented dummy developed for this work were used to measure experimentally the voltage values that could appear at some points of a human body and the currents due to the potential rise inside the shelter.

A. Instrumented dummy

To represent situations as real as possible, an instrumented dummy was designed and implemented. This dummy has the approximate dimensions and weight of a real person of about 80 kg. The electrical resistance of the human body of approximately 1 kΩ [41] was considered and included. The dummy was placed inside the proposed shelter in two positions, lying down and in a crawling position to measure the voltages due to the lightning impulse currents.

The design of the dummy considered joints to allow its limbs movement. This was important to achieve the lying down and crawling positions inside the shelter. Figure 4-16 shows the modeling design and construction of the dummy. The dummy was instrumented with several home-made resistors to conform the overall 1 kΩ impedance, and with home-made potential dividers to measure voltage differences between body parts: hand-to-hand, hands-to-knees, and head-to-feet for the two considered positions of the dummy.

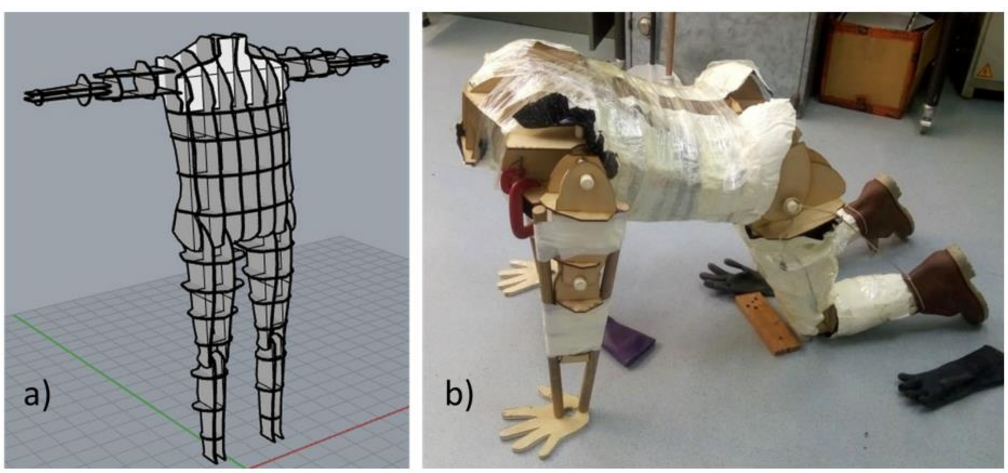


Figure 4-16. a) Development of the software model and b) the implemented base dummy.

B. Experimental set-up

A lightning impulse current pulse generator (LICG) with an approximate waveform of 8/20 µs with current values of the order of 1 kA up to 10 kA was used. The 8/20 µs waveform is a standardized shape, commonly used to characterize the currents from an indirect lightning stroke, specified by IEC 62305-1 and IEC 62305-4 standards for testing purposes [19], [37]. The current was applied on the ungrounded floor, entering at one point of the entrance edge of the tent and exiting at a point on the opposite side, to simulate a lightning current flowing through the entire base of the shelter. The voltages between some parts of the dummy were measured to determine the potential rise at points of contact of the body on the surface of the base tent.

The schematic set-up, the shelter view, and settings of the dummy inside the tent are presented in Figure 4-17 and Figure 4-18, where it is possible to see the entrance and outer points of lightning impulse current on the shelter floor and some of the used instrumentation.

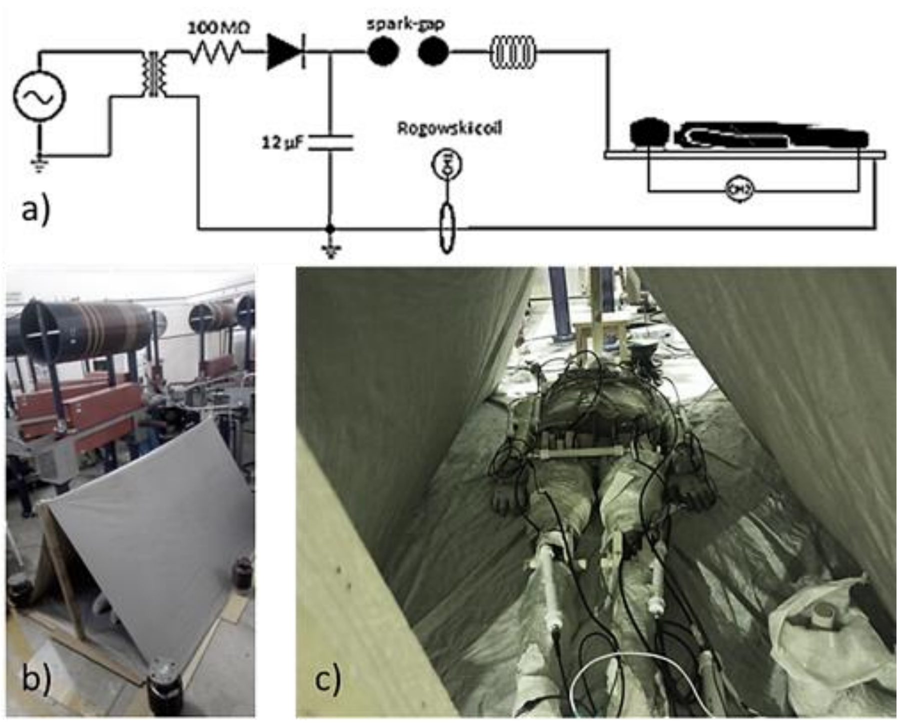


Figure 4-17. Experimental set-up for lying down position showing a) the schematic circuit, b) shelter outside view in the LICG laboratory, and c) interior view of the shelter with the instrumented dummy.

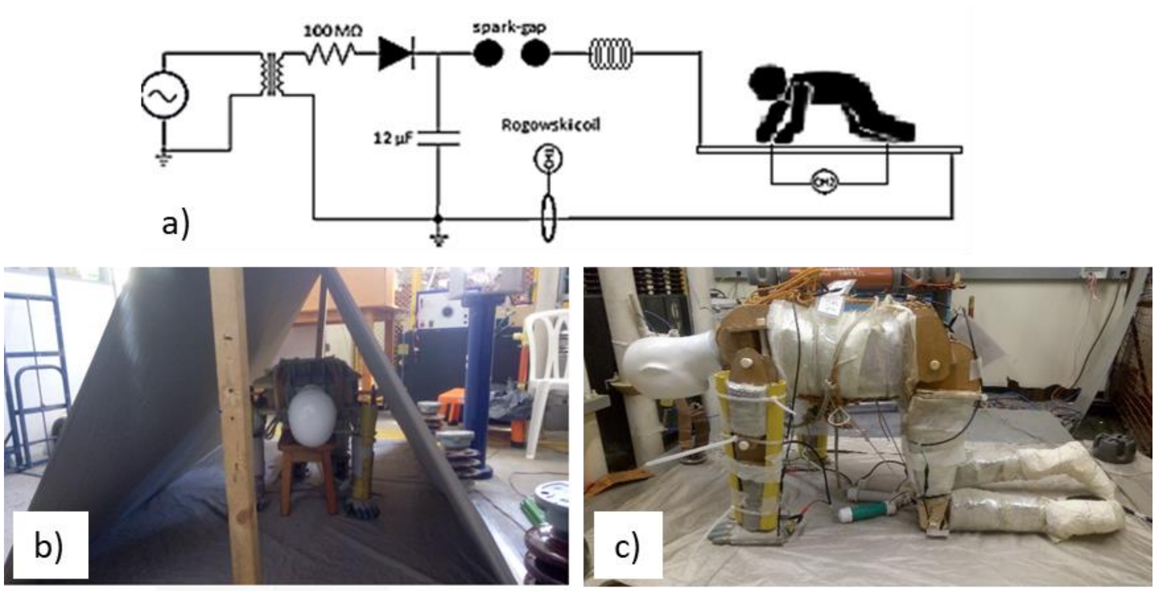


Figure 4-18. Experimental set-up for crawling position showing a) the schematic circuit, b) shelter inside view, and c) lateral view of the dummy.

C. Software simulation

It was used COMSOL Multiphysics® Software to perform mathematical simulations of the shelter considering a homogeneous soil, the A-frame shape of the shelter placed in the middle of the considered area, and a simplified body model inside the shelter (phantom), as it is shown in Figure 4-19.

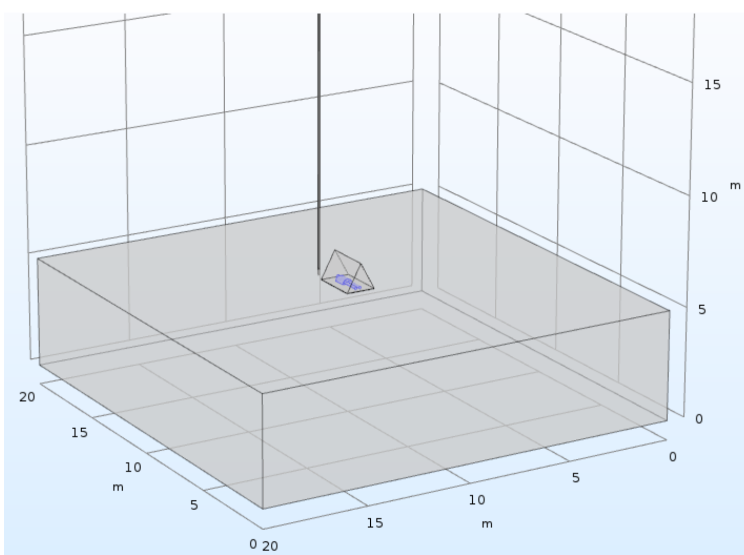


Figure 4-19. Basic modelling of the shelter in an homogeneous soil with a mannequin inside to estimate the potentials difference in the simplified body model. The lightning channel is represented as a perfect conducting bar.

For the electromagnetic simulations, the lightning strike point was considered at 3 m distance in the vicinity of the proposed shelter, with a channel current of 20 kA peak and a standard waveform of 8/20 µs. To model the homogeneous soil, a resistivity value of 100 Ω·m (i.e., σ = 0.01 S/m) and relative permittivity of εr = 40 were used, values that can represent a wet soil [67], [175]. These values were taken considering a typical situation of a lightning incident that may occur on a rainy night [69]. The human body (phantom) was modeled with basic geometrical shapes (cylinders and a half cylinder for the trunk) considering only the electrical tissue properties of the human skin [113].

4.4.5 Results and discussion

A set of measured voltages on the dummy are plotted in Figure 4-20. This plot corresponds to the voltages that appear inside the lightning shelter, after applying lightning current pulses of 8/20 µs, according to setup of Figure 4-17.

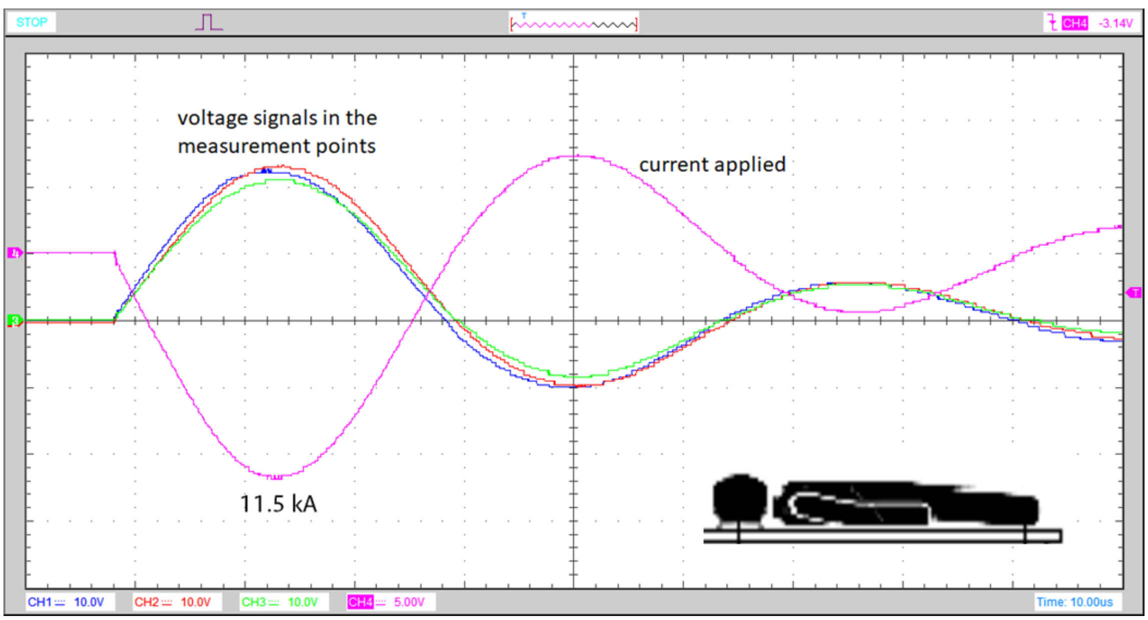


Figure 4-20. Plot of measured voltage signals at three points of the dummy base (head-to-feet, head-to-hand, and hand-to-feet), resulting of the applied of 11.5 kA 8/20 µs current impulse. The maximum amplitud voltage was 578 V between head-to-feet. Note that measurement scales are different for each signal channel.

Table 4-5 presents the potential differences between head to feet measured in the different tests for different applied lightning current pulses to the shelter. It is also included an important parameter in lightning analysis so-called as specific energy (or action integral). The specific energy is related to the energy per unit of resistance at the point of impact of the lightning channel. It can be said that specific energy (a.k.a. action integral or prospective energy) is the energy dissipated by a 1 Ω resistor when a lightning current passes through it [6]. If the current is high enough, the specific energy can produce a phase change in the material and melt the conductor. The head-to-ref impedance refers to the total impedance seen by the LICG, between the common point of the head and the fabric, referred to the ground reference of the generator to calculate de specific energy.

Table 4-5. Current and voltages measured inside the shelter for lightning impulses of 8/20 µs for the lying down position.

Polarity	I max [kA]	Max volt. head-to-feet [V]	Impedance head-to-ref (1) [Ω]	Specific energy [J/Ω]
+	7.2	403	0.42	567.25
+	9.5	492	0.41	1006.14
+	11.5	578	0.41	1427.57
-	7.1	274	0.41	575.03
-	9.5	427	0.40	996.15
-	11.5	515	0.40	1454.15

Note (1): refers to the ground reference of the current generator

Initial stages of melting of the ECF due to lightning currents are manifested on the fabric surface as scratches that appear perpendicular to the current flow [30], [176]–[178]. In Figure 4-15 a) it is possible to see in the micrograph the scratches formed on the surface of a rip-stop fabric after some lightning impulse tests. In previous tests it was shown that for ECF samples of 10 x 10 cm, at 10 kA and above, the melting process is initiated [30], [177].

Considering an approximate resistance for the human body of 1 kΩ [41] and from the potential differences measured between the points in contact of the dummy with the lightning shelter floor, the energy to which a person would be subjected under similar conditions was estimated. Table 4-6 shows the maximum estimated energies for the lying down position inside the shelter. The estimated energies for the dummy are in the order of few hundred of microjoules, in all cases indicated in the Table 4-6 as < 1 J. An energy of 10 joules is considered as the energy necessary to initiate a fibrillation process that can lead to death [41], [44].

Table 4-6. Maximum voltages and estimated energy level inside the shelter for the lying down position.

Points of measurement	Maximum current (kA)	Maximum voltage (V)	Energy (J)
Head-to-feet	+ 11.5	578	< 1
Hand-to-feet	+ 11.5	193	< 1
Head-to-hand	+ 11.5	347 384	< 1

From the software simulation results, it was possible to get the electrical surface potentials with a lightning current of 20 kA peak was applied. Figure 4-21 shows the surface potential distribution as equipotential lines for the wet soil considered.

It can be observed that the proposed shelter model behaves as an electrical conductor with higher conductivity than the soil, producing changes in the distribution of equipotential lines on the surface. This means that the proposed shelter model has an equipotential body behavior (like a Faraday cage), when the ground potential increases due to the lightning currents diverted in the ground.

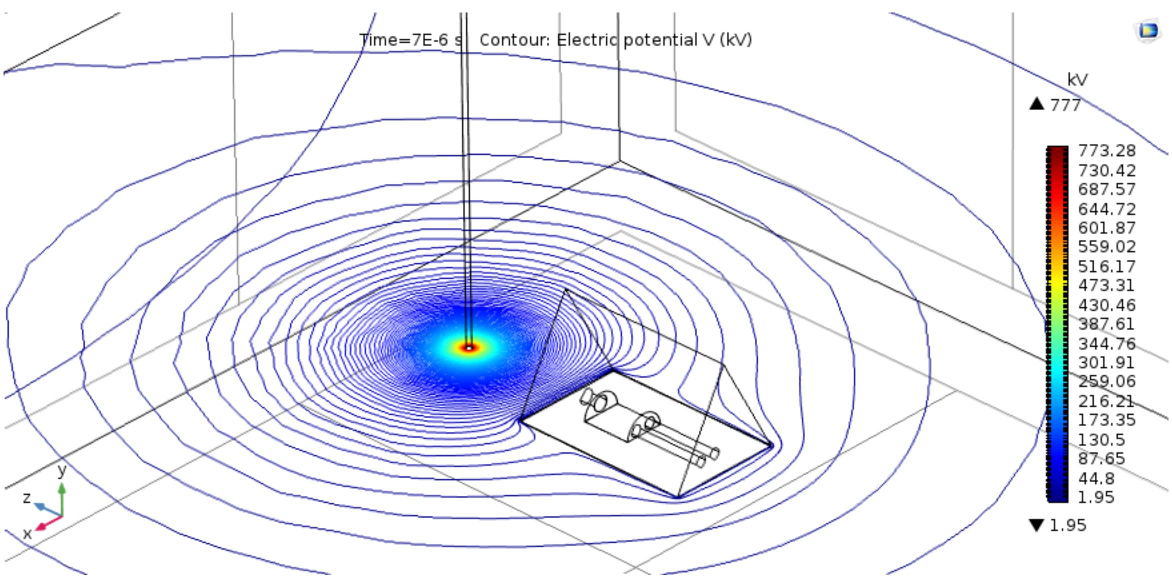


Figure 4-21. Equipotential lines around the lightning strike point and the proposed shelter with the human phantom inside.

By the nature of the atmospheric electrical discharge and its distribution on the ground, the current can be considered uniformly distributed assuming a homogeneous soil and the absence of ionization on the ground. Therefore, the total lightning current would be diverted in all directions from the strike point, so the shelter would only be subjected to a fraction of the total lightning current.

The proposed shelter allows directing the currents externally to the human body and would behave as an equipotential surface. Due to the low resistance of the ECF material, in the order of a few tens of milliohms, the voltage between the contact points would be reduced. The results from laboratory measurements show that the voltages inside the shelter against lightning impulse currents are considerably lower than those that could be experienced by a person without any type of protection. A significant reduction in the voltages reduces the energy a person is subjected to, mitigating the risk of permanent injury or even death.

Moreover, the result of the computational simulations also shows, for the conditions considered, that the potential difference experienced by the body (phantom) inside the shelter would not represent a considerable risk to human health. Figure 4-22 shows on a color scale the potential within the shelter floor, with red indicating 30.21 kV and blue 30.13 kV. This for the modeled body represents about 80 V, which can be easily isolated with a thin layer of any type of insulation.

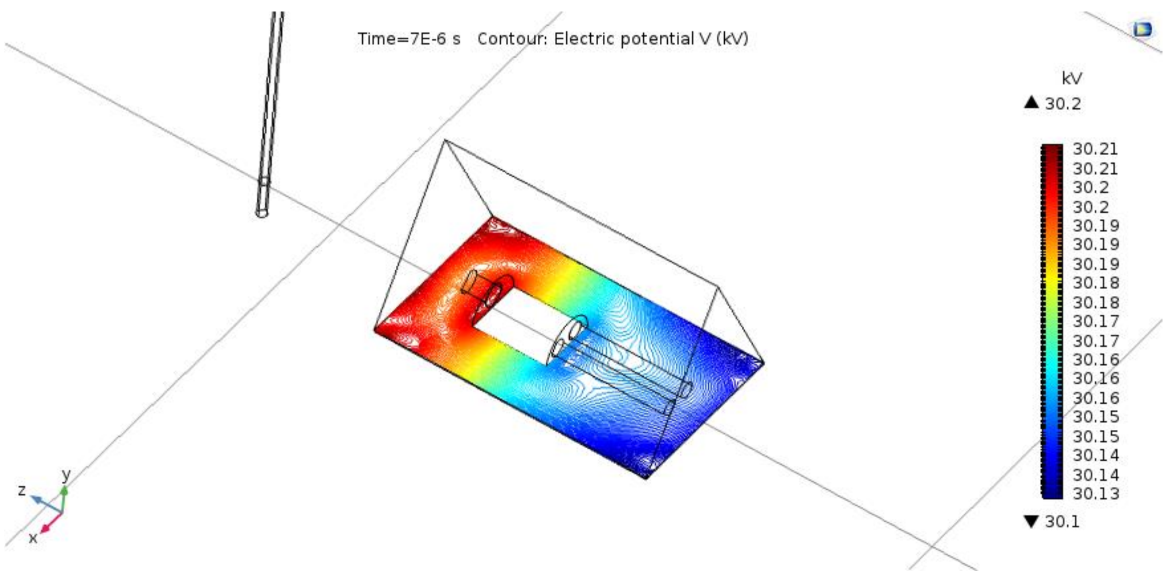


Figure 4-22. Difference of potential inside the shelter floor.

The values of laboratory and computational simulation results show that it is possible to reduce the potential rise inside the shelter to values below 600 V from lightning currents up to 12 kA. This voltage levels can be easily insulated with conventional materials that do not require high dielectric strength. On the other hand, calculated energies showed values lower than 1 joule. Due to their short duration and amplitude, those energies would not have a significant effect on the health of a person placed inside the shelter.

It is important to note that the same lightning shelter model endure more than 40 subsequent high current impulses during the development of this research.

4.4.6 Conclusion

The conducted laboratory tests show that the electroconductive fabric used for the construction of the proposed lightning shelter allows an effective implementation of the equipotentialization concept for protection due to its very low electrical resistance and its great ability to conduct large lightning currents that are distributed over its entire surface. The material can conduct several lightning impulses without suffering important affectations in its structure and electrical characteristics.

The proposed lightning shelter, which uses an electroconductive fabrics, reduces the potential differences between the contact points of an individual inside the shelter, reducing the risk of significant injury or death by ground currents, responsible for most of lightning-caused fatalities.

4.4.7 Acknowledgment

The authors would like to thank for all the work and support in the development of this project to Eng. MSc. Edwin Pineda, Eng. MSc. Daniel Rodríguez, Eng. MSc. Carlos Rivera, ID. MSc. María Barajas, Laboratorio de Ensayos Industriales – LABE of Universidad Nacional de Colombia – UNAL, and to *Escuela de Logística del Ejército Nacional de Colombia* – EJC.

4.5 Other own work related to lightning current tests on electroconductive fabrics and personal lightning protection

Related work to personal protection against lightning that were presented in Colombian and international congresses, symposiums, and journals are listed in the Table 4-7 below.

Table 4-7. Presented or published works related to this thesis on personal lightning protection.

Event or congress	Title	Place and data
XIII SIPDA, 2015	Nonfatal Lightning Injuries in Colombia: Case Reports [39]. International Symposium on Lightning Protection (SIPDA) DOI: 10.1109/SIPDA.2015.7339328.	Balneário Camboriú, SC- Brazil, 28th Sept. – 2nd Oct. 2015
33 ICLP, 2016	Characterization of a Metallic Pearl-like Necklace stroked by lightning: preliminary results [119]. International Conference on Lightning Protection (ICLP) DOI: 10.1109/ICLP.2016.7791466.	Estoril – Portugal, 25th Sept. – 30th Sept. 2016
33 ICLP, 2016	Determination of the Lightning Current from its Thermal Effects [120]. International Conference on Lightning Protection (ICLP). DOI: 10.1109/ICLP.2016.7791464	Estoril – Portugal, 25th Sept. – 30th Sept. 2016
EPSR Journal, 2016	Analysis of two nonfatal lightning accidents in Colombia [170]. Electric Power Systems Research (EPSR) 153 (2017) 159–169 DOI: 10.1016/j.epsr.2016.12.021. **JOURNAL.**	EPSR, 153 30th Dec., 2016
XIV SIPDA, 2017	Fatal livestock lightning accident in Colombia [65]. International Symposium on Lightning Protection (SIPDA) DOI: 10.1109/SIPDA.2017.8116939	Natal, RN- Brazil, 2nd Oct. – 6th Oct. 2017
XIV SIPDA, 2017	Lightning Fatalities in the Livestock Industry in Colombia. International Symposium on Lightning Protection (SIPDA). *Unpublished work.*	Natal, RN- Brazil, 2nd Oct. – 6th Oct. 2017
III Encuentro Internacional de Ciencia y Tecnología para el Desminado Humanitario, 2017	Protección contra rayos en actividades de desminado humanitario. III Encuentro Internacional de Ciencia y Tecnología para el Desminado Humanitario, 2017. *Unpublished work.*	Medellín – Colombia, 26th Oct. – 27th Oct. 2017
2018 ICEAA	High Current Tests Over Conductive Fabrics [30]. 2018 International Conference on Electromagnetics in Advanced Applications (ICEAA). DOI: 10.1109/ICEAA.2018.8520351	Cartagena de Indias – Colombia, 10th Sept. – 14th Sept. 2018
Seminário CENDAT, IEE/USP, 2018	Estudo sobre proteção pessoal contra descargas atmosféricas. Centro de Estudos em Descargas Atmosféricas e Alta Tensão (CENDAT), Instituto de Energia e Ambiente da Universidade de São Paulo (IEE/USP). *Unpublished work.*	Sao Paulo, SP – Brazil, November 29, 2018
XV SIPDA, 2019	Conductive Fabric Potential Rise due to Lightning Impulse Currents [25]. International Symposium on Lightning Protection (SIPDA). DOI: 10.1109/SIPDA47030.2019.8951605	Sao Paulo, SP – Brazil, 30th Sept. – 4th Oct., 2019
XV SIPDA, 2019	Lightning Incident with Multiple Natives Injured in the Sierra Nevada de Santa Marta - Colombia: Description of Scenario [26]. International Symposium on Lightning Protection (SIPDA) DOI: 10.1109/SIPDA47030.2019.8951570	Sao Paulo, SP – Brazil, 30th Sept. – 4th Oct., 2019
ACES, 2020	Thermal simulation of a conductive fabric sheet subjected to a lightning-like current [179]. 2020 International Applied Computational Electromagnetics Society (ACES) Symposium. *Unpublished work.* DOI: 10.23919/ACES49320.2020.9196041	Monterey, CA – United States, 22th Mar. – 26th Mar., 2020

Event or congress	Title	Place and data
URSI GASS, 2020	Model for the Estimation of Partial Burst of Ripstop Electro-Conductive Fabrics [176]. XXXIIIrd General Assembly and Scientific Symposium (GASS) of the International Union of Radio Science (URSI) DOI: 10.23919/URSIGASS49373.2020.9232413	Rome, Italy, 29th Aug. – 5th Sept., 2020
PIER C Journal, 2020	Specific Action as a Metric to Determine Thermal Degradation of Conductive Fabrics Exposed to High Current Impulses [180]. PIER C: Progress in Electromagnetic Research C, Vol. 105, 59-72, 2020 DOI: 10.2528/PIERC20052301. **JOURNAL**.	PIER C, 105 2nd Sep., 2020
35 ICLP – XVI SIPDA, 2021	10/350 µs Lightning Impulse Current Behavior of a Conductive Fabric [178]. 35th International Conference on Lightning Protection (ICLP) and XVI International Symposium on Lightning Protection (SIPDA) DOI: 10.1109/ICLPandSIPDA54065.2021.9627391	Colombo – Sri Lanka, 20th Sep. – 26 Sep., 2021
35 ICLP – XVI SIPDA, 2021	Revisiting a case of lightning-caused trauma in a pregnant woman [181]. 35th International Conference on Lightning Protection (ICLP) and XVI International Symposium on Lightning Protection (SIPDA) DOI: 10.1109/ICLPandSIPDA54065.2021.9627467	Colombo – Sri Lanka, 20th Sep. – 26 Sep., 2021
JART Journal, 2022	Lightning Impulse Current Tests on some Electroconductive Fabrics (preprints in [147], [148]). Accepted for publication in Journal of Applied Research and Technology on May 9, 2022. **JOURNAL**.	JART, 2022
36 ICLP, 2022	Personal protection against lightning using electroconductive fabrics. 36th International Conference on Lightning Protection (ICLP). *Unpublished work.*	Cape Town, South Africa, 2nd Oct. – 7 Oct., 2022

On the other hand, three main projects were developed in the frame of this thesis:

Table 4-8. Developed projects in the frame of this thesis.

Call of proposal	Title of the approved project	Code, place, and year
"UN INNOVA": *Convocatoria de Proyectos para el Fortalecimiento de la Innovación en la* Universidad Nacional de Colombia *a Partir del Desarrollo de Prototipos y Experiencias Piloto* 2016-2018	*Refugio portátil multifuncional para la protección contra los rayos y el suministro de energía eléctrica* (Multifunctional portable shelter for lightning protection and for electrical power supply). *Modalidad 3: Propuestas de prototipos o escalamientos, presentadas por grupos de investigación en alianza con empresas del sector productivo o solidario, hasta por treinta millones de pesos* (Category 3: Proposals for prototypes or scaling up, submitted by research groups in alliance with companies of the productive or solidarity sector, for up to 30 million pesos).	Hermes 36748, Bogotá, D.C., Colombia, 2017
Convocatoria Nacional de Proyectos para el Fortalecimiento de la Investigación, Creación e Innovación de la Universidad Nacional de Colombia 2016-2018	*Diseño e implementación de un refugio portable, que permita la protección contra descargas eléctricas atmosféricas (rayos) y que mitigue el riesgo a la salud de sus usuarios para preservar su vida e integridad física* (Design and implementation of a portable shelter to protect against atmospheric electric discharges (lightning) and to mitigate the risk to the health of its users to preserve their life and physical integrity). *Modalidad: única* (Category: unique)	Hermes 37658, Bogotá, D.C., Colombia, 2018

Call of proposal	Title of the approved project	Code, place, and year
Convocatoria Interna 002 de 2018, Escuela de Logística del Ejército Nacional de Colombia.	*Validación de un prototipo de refugio portable, que permita la protección contra descargas eléctricas atmosféricas (rayos) y que mitigue el riesgo a la salud para preservar la vida e integridad física del usuario final* (Validation of a portable shelter prototype, which allows protection against atmospheric electrical discharges (lightning) and mitigates the health risk to preserve the life and physical integrity of the end user). *Instituciones participantes* (Institutions involved): *UNIVERSIDAD NACIONAL DE COLOMBIA – Sede Bogotá (*UNAL*), EJERCITO NACIONAL – ESCUELA DE LOGISTICA* (School of Logistics of Colombian National Army - EJC)	Hermes 44296, Bogotá, D.C., Colombia 2019 - 2021

As shown, for the development of this thesis there was a strong collaborative relationship with the School of Logistics of the Colombian National Army (EJC) with information and financial assistance through a project.

Following is presented some additional work carried out during the execution of this research to try to understand some observed phenomena and validate the behavior of the proposed model of the shelter against lightning-type currents.

4.5.1 Lightning currents on a reduced model of the proposed shelter

Despite the proposal model for lightning protection is not intended at first instance to protect against direct lightning currents, it was performed two subsequent 20 kA direct strike tests considering the A-frame shelter model presented previously (see Figure 4-15 b of section 4.4.3). It was used the electroconductive ripstop fabric folded and sewn with flat felled seams (code 2.04.03) using cotton threads, forming the closed A-frame shown in Figure 4-23 with dimensions in mm to obtain a model scale of 1:10. The base was grounded and the two 8/20 μs standard impulses were applied on the shelter ridge, the first close to the middle and the second at one end, recording current and voltage. Figure 4-24 shows some images related to the test process and Figure 4-25 shows the plots for both tests.

Current and voltage plots of Figure 4-25, recorded for the reduced model, shows that the behavior is quite resistive as the voltage follows the applied current, similar to that of Figure 4-13 for the test of 5 kA on the 10 cm sample. However, a voltage lag after the peak value of the current is also clear, which could be thought of as an inductive component but end in phase with the current pulse.

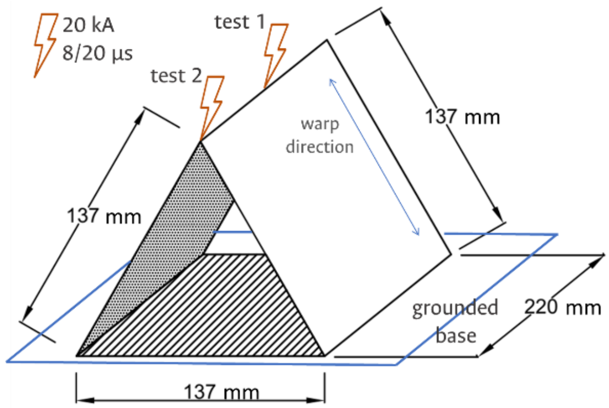


Figure 4-23. Lightning tests with 20 kA – 8/20 µs wavewshape were done over an A-shape model of 1:10 scale, mesuring the voltage between the applied point and the grounded base.

Figure 4-24. Images of 1:10 scaled A-shape tent model during the test process, a) previous to the first 20 kA test at the center of the ridge, b) after the first test with the notorious concentric mark, c) after the second 20 kA test at one end of the ridge showing the surface marks around the entry points, and d) the model base after the two current impulses.

Considering the resistance value, i.e. the Ohm's law, at the peak of the applied current, for the first 20 kA test the resistance was estimated in 8.5 mΩ, while for the second 20 kA test, the resistance was 14.2 mΩ as shown in Table 4-9. Considering the geometry of the tent model, with the two sides in parallel, and the base connected to the ground plane at 0 Ω, then, the equivalence factor is 2 x 220/137 which is about 3.21. As shown in Table 4-9, the dynamic-like equivalent resistance for the first 20 kA test is 27.2 mΩ/□, and 45.6 mΩ/□ for the second one.

Both voltage and current characteristic give the dynamic resistance behavior of the fabric and ultimately the shelter. The resistive plots in Figure 4-25 (c and d) highlight the variations that may due, on the one hand, to the phase change of the conductive material and, on the other hand, to the change in mechanical resistance due to the shock wave on the surface of the tent roof.

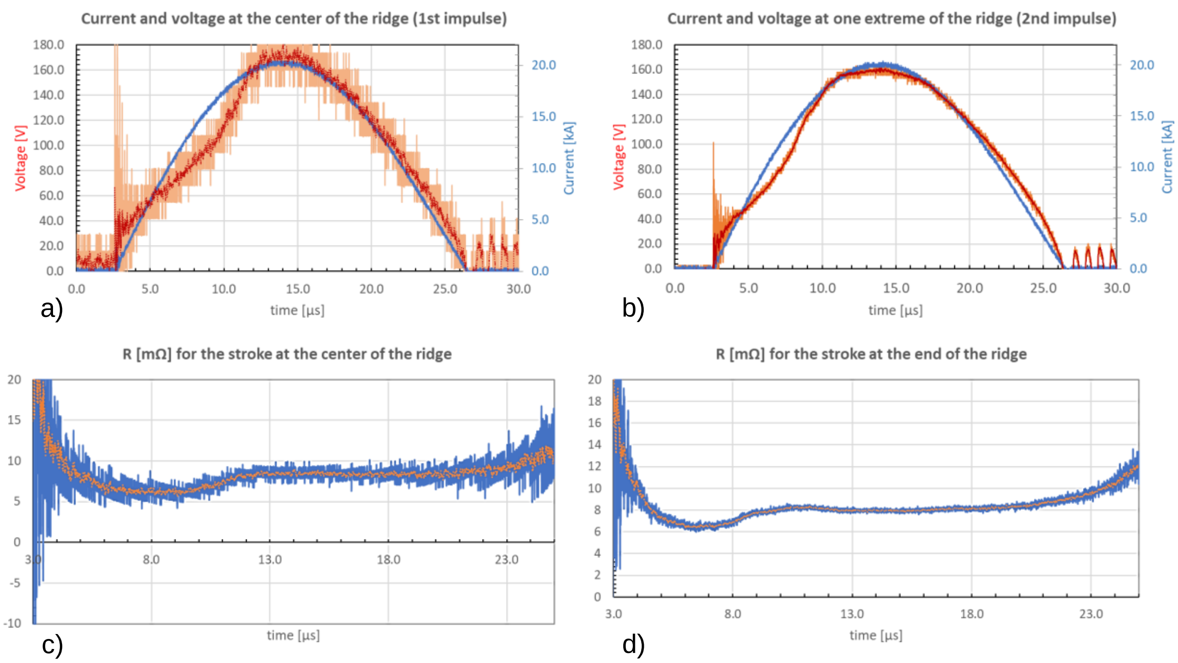


Figure 4-25. Current and voltage plots of the same shelter model tested for 20 kA current impulses applied at the center of the tent ridge (a) for the first test and for the second test at one end of the tent ridge (b); and the corresponding estimated resistance plots for both tests (c and d). Note that -b- and therefore -d- have better measurement resolution than -a-; although they are not equal, both voltage measurements in -a- and -b- have similar behavior, approximately between 160 V and 170 V peak. Both voltage and resistance plots have moving average trendlines of a 10-data points window.

Table 4-9. Voltage and resistance estimated for the two 20 kA tests on the same reduced model.

Voltage and resistance at peak value of the current for the reduced model				
	current peak kA	measured voltage V	estimated resistance mΩ	equivalent for a square mΩ/□
first test	20.2	171.0	8.5	27.2
second test	20.0	283.0	14.2	45.6

As previously reported and as shown particularly in Figure 4-4 and Figure 4-12, above a certain level of current, the tested conductive fabric exhibited a noticeable change in its surface by color change and scratches perpendicular to the current flow. As can be seen in Figure 4-26, the concentric burned marks centered around the entry points at the shelter ridge are also perpendicular to the current flow, assuming the even distribution of the current, from the contact point towards the outside.

Mechanically, the scaled shelter model endures the two lightning impulses suggesting that it is possible to use rip-stop conductive fabrics in personal lightning protection systems to mitigate lightning risks in outdoor applications such as tents and mobile shelters.

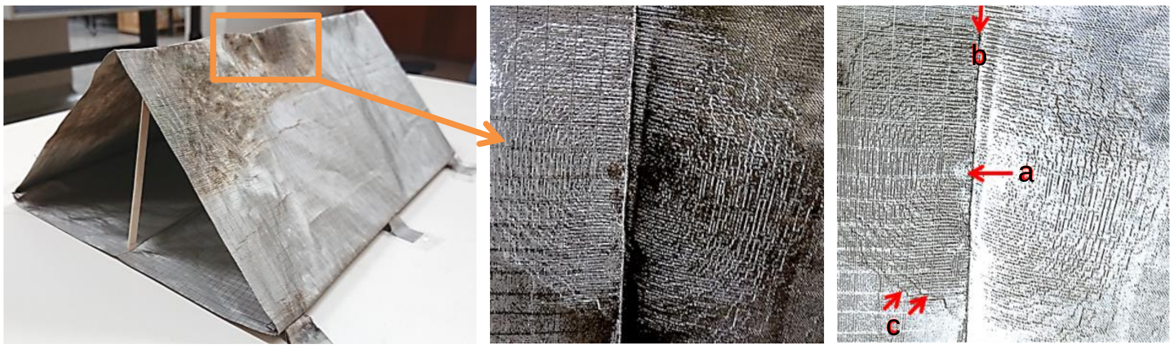


Figure 4-26. Reduced model tent after the two 20 kA tests (a), and positive (b) and negative (c) zoom image of a section of the conductive rip-stop fabric after the applied impulsive current at the entry point c)-a- over the ridge c)-b- of a 1:10 scaled A-frame shelter model, letting concentric marks c)-c-.

4.5.2 Other lightning impulse tests on rip-stop electroconductive fabric samples

8/20 µs LICs tests

To asses the behavior and current flow capacity of the used rip-stop electroconductive fabric, complementary tests were done at the Lightning Laboratory of IEE/USP in Brazil. Several 8/20 µs impulse current up to 20 kA were applied on several samples of 10 x 10 cm following the methodology and using the equipment shown in section 4.3 [177]. At Uppsala University (Sweden), additional tests led by Prof. Román were performed with impulse currents of 10/350 µs and different amplitudes up to 88 kA over samples of 30 cm x 30 cm, as described in [178]. The fabric is the same rip-stop type used in all the published and this manuscript, reported previoulsy in Table 4-2 as the fabric F1.

The following Table 4-10 lists the voltage measurements for each peak value of the lightning current for one fabric sample, the estimated resistance, and the estimated surface current density $K(t)$ considering the width of the sample.

Table 4-10. Voltage and estimated resistance for the tests on rip-stop samples of 10 cm x 10 cm.

Voltage and resistance at peak current value for the 10 × 10 cm samples			
current peak kA	measured voltage V	estimated resistance mΩ	surface current density A/cm
5.2	155.4	29.8	520
7.5	243.1	32.3	750
10.0	395.3	39.3	1000
14.6	300.9	20.5	1460
19.2	241.3	12.6	1920

In Figure 4-27 are plotted the voltage measurements and resistances estimates at the peak values of the five applied current levels. It is evident that around 10.0 kA occurs a change in the current conduction behavior through the fabric surface. Similar to what was discussed in section 4.3.4 above, for 5.2 kA, 7.5 kA and even for a 10.0 kA test, the fabric showed a ohmic behavior, with voltage following the applied current. For the 5 kA tests no appreciable changes in its surface area were observed.

The change after 10 kA peak current suggests another conduction mechanism, perhaps a plasma conduction phenomenon likely due to a loss of conductive material from the surface, creating bridges as discussed towards the end of section 4.2.6.

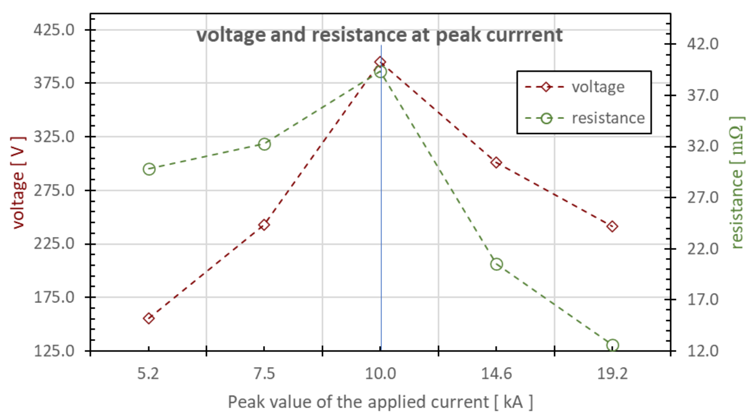


Figure 4-27. Voltage and resistance vs. the peak value of the applied current for 5 current amplitudes.

High voltage tests

Prior to the high current tests, several preliminary high-voltage (HV) tests were performed to evaluate the paths that the currents could follow through the models. Figure 4-28 shows two images of HV tests over a lightning shelter model.

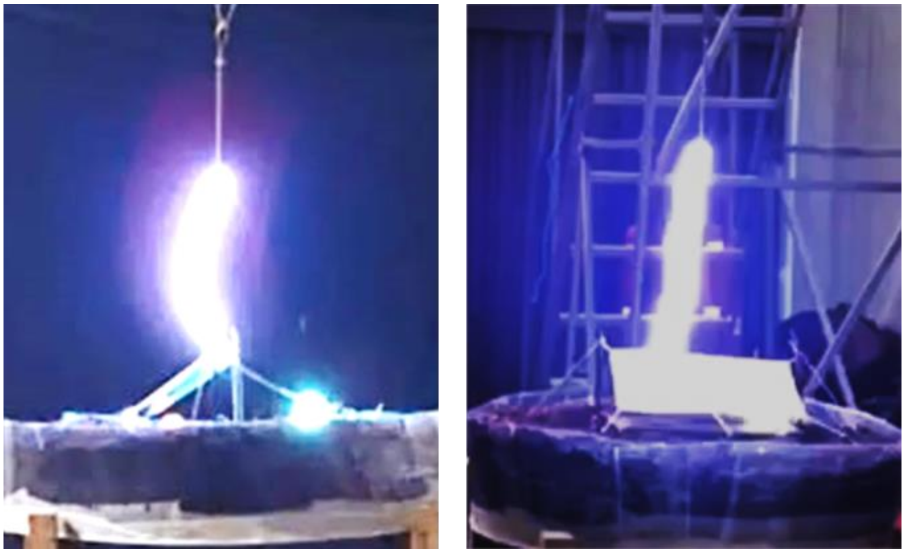


Figure 4-28. Front (left) and lateral (right) views of 300 kV tests over a tent model simulating direct lightning strikes. The roof and base were made of electroconductive fabrics to guide the currents to the ground.

The tent model was tested on the Marx Voltage Impulse Generator of the LABE at Universidad Nacional de Colombia. 300 kV to 400 kV impulses with an electrode spacing of about 20 cm were used to simulate lightning paths. Since in a HV test the currents are of very low amplitude compared to an actual lightning strike, there was no observable changes in the electroconductive fabric surface, so there was no damage to its surface.

HV tests on the reduced tent model suggest that the electroconductive fabrics used to form the roof and base can safely divert the currents to the ground, protecting the users inside.

4.5.3 Conduction mechanisms over the conductive fabric

As in other LIC tests performed with 8/20 μs standard currents, in consecutive 10/350 μs LIC tests performed in Uppsala, Sweden [178] on 30 cm x 30 cm rip-stop fabric samples, changes in the surface fabric were evident mainly in the form of scratches and darkening of the fabric surface color. 10/350 μs waveforms somewhat considers the energy and charge that could have a lightning with continuous currents.

Figure 4-29 shows pictures of the fabric side designated as “frontside” after each impulse of a series of five consecutive tests with 10/350 μs LIC tests performed in Uppsala, with peak current amplitudes of 24.5 kA, 19.9 kA, 17.5 kA, 19.1 kA, and 16.4 kA. The first LIC test of 24.5 kA left scratches perpendicular to the current flow on the fabric surface. Each consecutive test darkened the surface of the fabric and formed connective channels between the two electrodes, most easily observed in the last two tests at 19.1 kA and 16.4 kA. In fact, in the final test the fabric was split in two parts, across the formed channel towards the center of the sample. The consecutive tests suggest the current conduction in two ways, evidenced as horizontal scratches and vertical channels.

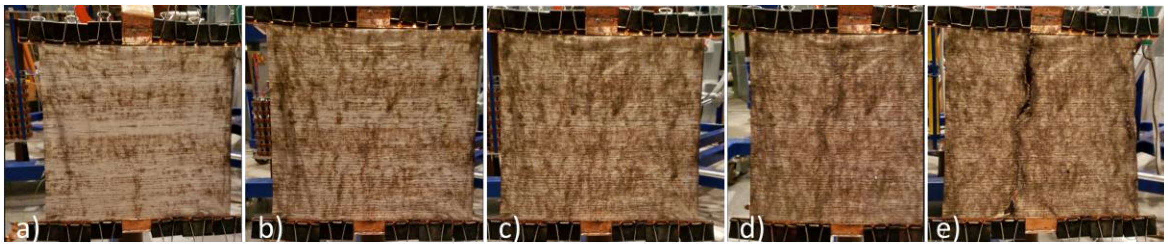


Figure 4-29. Images of the frontside of a 30 cm x 30 cm ripstop sample after consecutive LIC tests with 10/350 μs currents of a) 24.5 kA, b) 19.9 kA, c) 17.5 kA, d) 19.1 kA, and e) 16.4 kA. Note the formation of connective channels between electrodes that finally split the sample (e).

These two non-obvious current mechanisms were corroborated via still and ultra-high speed at 100 kfps cameras pointed at the backside of the sample. Figure 4-30 shows the captured snapshots of the same sample during two of five consecutive high current tests. Therefore, in the tested fabric, there are three mechanisms for conducting current: 1- ohmic conduction, 2- plasma formed across the transverse scratches in “crosswise asperities”, and 3- plasma formed between both electrodes.

Previously, in the section 4.2.6 was discussed the first and second conduction mechanisms. If the dissipated energy is not enough to melting the conductive materials, the conduction is given through the intrinsic charge carriers of the material itself in compliance with Ohm’s law (first mechanism). If the formed crosswise asperities result in full horizontal gaps with not paths to the current, the conduction take place through plasma as dielectric strength is overcome, jumping the crosswise gaps (second mechanism). The formation of lengthwise plasma channels or arcing between electrodes as shown in Figure 4-30 (c and d) could occur when the interstices increase in number and spacing, and the local electric field is not high enough to produce an electrical breakdown between them. However, as after consecutive tests the surface can accumulate carbonized material from the polyester core and ejected conductive particles, this mixture could give tracking paths to the current between the two electrodes until arcing (third mechanism).

Strictly speaking, a conductive fabric is a volumetric material, therefore, governed by the charge density continuity equation given in Eq. 14,

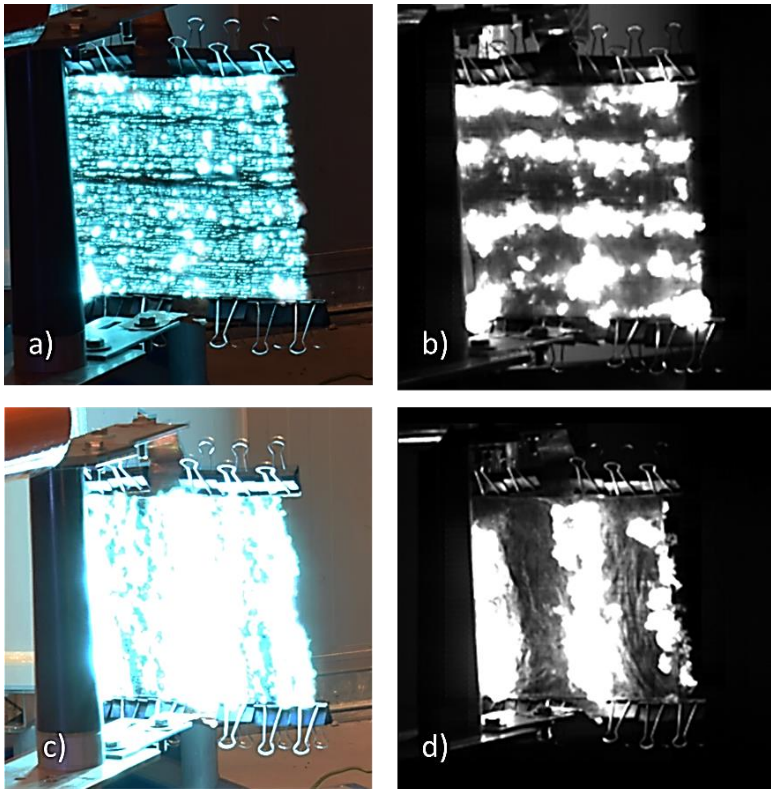


Figure 4-30. Snapshots from still (left) and ultra-high velocity @ 100 kfps (right) cameras of 10/350 µs tests on a 30 cm x 30 cm ripstop electroconductive fabric sample, a) and b) during the first 24.5 kA LIC test, and c) and d) in the course of the subsequent fourth 19.1 kA test.

$$\nabla \cdot \vec{J} + \frac{\partial \rho}{\partial t} = 0, \qquad \text{Eq. 14}$$

where $\vec{J}$ is the volume current density (in A/m^2), ρ the volume charge density, and t the time. Considering the surface and internal currents of the conductive material, Eq. 14 leads to an equivalent surface continuity equation given by Eq. 16

$$\vec{n} \cdot \Delta\vec{J} + \nabla_S \cdot \vec{K} + \frac{\partial \sigma}{\partial t} = 0, \qquad \text{Eq. 15}$$

where $\vec{n} \cdot \Delta\vec{J}$ is the interface divergence of volume current density of both interface sides with $\vec{n}$ the normal unity vector, $\nabla_S \cdot \vec{K}$ is the surface divergence of $\vec{K}$, and σ is the surface charge density [182]. If the entire current is considered to flow on the surface, $\vec{n} \cdot \Delta\vec{J}$ can be neglected.

The current flow on a thin surface, such as in a conductive sheet, can be considered as a surface current density $\vec{K}$ related to the tangential electric field strength $\vec{E_t}$ at the conductive surface with conductivity Γ [182], in a form of the Ohm's law given by Eq. 16. The units of $\vec{K}$ are A/m.

$$\vec{K} = \Gamma \overrightarrow{E_t} \qquad \text{Eq. 16}$$

Considering the geometry of the used samples of ripstop electroconductive fabric (ECF) with 80 µm thickness and 10 cm wide (see micrographs of Figure 4-2), a ratio of 125 X (i.e., $10^{-3}/80^{-6}$) is obtained, well enough to take the used ECF as conductive thin films. However, for Lightning Impulse Current (LIC) tests, small variations or inhomogeneities in the electrical resistance of the fabric, or otherwise of the conductivity Γ, can have substantial effects on its surface. It was shown using the so-called specific action method that the contact resistance between warp and weft yarns is expressive particularly in low resistance fabrics when a large current flows through them and high energy dissipation is expected [180].

Therefore, a sheet of electroconductive fabric cannot always be considered as a thin, uniform and isotropic conductor largely due to the difference in the contact resistance between interlacing yarns [160], [183] (warp and weft in rip-stop ECF), but also in the manufacture process, uniformity of metal deposition on the fibers, stress, and mechanical deformation such as that produced by bending or wrinkling.

Moreover, after several high amplitude impulsive current tests, the degradation of the conductive mesh can lead to an increase of the electrical resistance due to local inhomogeneities of its structure due to the loss of material which led to inhomogeneous current distributions finally producing local overheating.

Current-carrying fibers

To elucidate what can cause the crosswise scratches on the surface of electroconductive fabrics when high currents flow through it, computer simulations were performed using a finite element analysis software to analyze the temperature change along the conductive fibers. For the single fiber model in Figure 4-31, constantan (55 % of copper and 45 % nickel) was considered as the outer conductor material and standard air for the core instead of polyester.

The results obtained reveal a temperature gradient in the fiber reaching about 120 °C, as shown in Figure 4-31, appreciable at the curvatures where the current changes its direction and current crowding effect (CCE) occurs. Considering a transverse cross section area of the fiber in a bend, the current density is not homogeneous, higher on the inside than on the outside of the bend, therefore, increasing the temperature where the current density is higher. The current density divergences become smaller as the distance to the bend increases. Straight conductors have no current density divergences, so the temperature is homogeneous over the entire surface. Of course, folds or wrinkles on the surface will have the same effect. It is worth mentioning that CCE is often considered for the development of power semiconductor.

By grouping several fibers in parallel, it is observed that isothermal patterns are formed, transverse to the direction of the applied current. Therefore, that change in temperature forming crosswise patterns could contribute to the formation of scratches in the ECF surface as seen in the images presented.

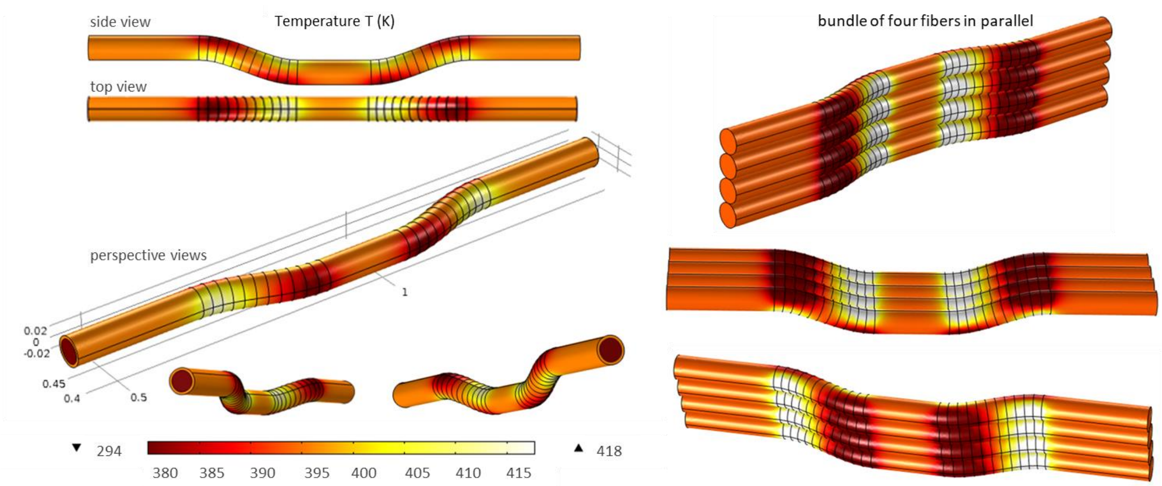


Figure 4-31. Computer simulation of the temperature in a single fiber (left) and in a bundle of four parallel fibers (right) with a temperature gradient of 124 K.

4.5.4 Considerations on the risks of occupational exposure to nickel compounds

The conductive sheat of the fabric studied and proposed for use in the shelter is composed of an approximatley 57-43 copper-nickel alloy, as shown in section 4.2. Despite the use of the shelter is not intended for prolonged use, occupational exposure to the compunds in the fabric has some risks. Since copper is an essential element of human metabolism, the risks to shelter user arise mainly from exposure to nickel.

The risks to people from occupational exposure to nickel compounds can be divided into three main categories [184]:

1. allergies; around 15 % of women and 2 % of men can develop nickel allergic contact dermatitis (NACD) from continuous or prolonged contact with the skin [185],

2. sinusitis, rhinitis, and other respiratory diseases [184]; by inhalation of dust particles,

3. cancer of the lungs, nasal cavities, and other organs; by exposition to an extremely high level of nickel or nickel carbonyl via inhalation [186].

To avoid any health issue related to nickel compounds, it is suggested to use an additional layer of insulating material, safe for human use, to insulate the conductive material from possible skin contact. This would also help to electrically insulate the conductive surface. On the other hand, as stainless steel fibers are usually coated with a thin layer of chromium oxide to prevent corrosion, it would also present some health concerns by having an irritating effect on some human tissues. The use of pure copper or silver fibres would avoid these drawbacks.

4.6 Concluding remarks

The proposed lightning protection model presented as a basic A-frame tent for personal use in outdoor conditions, made with Electroconductive fabrics (ECF) of very low resistivity, has been shown their potential use to reduce the risk of lightning currents, when exposure to atmospheric electrical activity in open fields is unavoidable. The suggested use of the rip-stop ECF has been demonstrated its ability to divert and withstand consecutive lightning currents particularly that produced by indirect coupling, through laboratory tests and the presentation of the results for evaluation by the international scientific community at journals, congresses, and symposia.

5. Conclusions and perspectives

5.1 Conclusions

Lightning maps show the uneven distribution of lightning activity around the world, revealing several hotspots and large areas more prone to lightning strikes on the ground. However, many reports of lightning injuries and deaths suggest that even areas with low lightning activity can pose significant risks to human health. Factors such as outdoor and remote places activities, which are currently on the rise, lack of proximity to or availability of medical help, geographical location, time of day, weather, climate, and season, all contribute to the variability that can worsen the risk.

Lightning protection is an invisible feature of our cities, particularly those in the developed world, but reducing the lightning risk to unavoidable exposed people around the world remains a major challenge. Many standards such as IEC 62305 and IEC 62561 series deal with lightning protection to structures, their installations, and contents. The technical report IEC TR 62713 gives some advice, recommendations, and procedures to reduce the risk and protect people against the deleterious effects of lightning. It is important to bear in mind that any avoidable loss of life is unacceptable, and taking any action to reduce the risk is worthwhile, regardless of the outcome of a risk assessment.

While prevention is the ultimate measure of lightning protection, certain human activities unavoidably expose people to the risk of lightning. Several reports and technical literature reveal that lightning currents through the ground that produce earth potential rise (EPR) is the most fatal coupling mechanism between lightning and people. Ground currents can cause superficial and deep burns, enter the body affecting several organs, cause hearth malfunction, fibrillation and can lead to death. It was shown from a Colombian National Army report that even underground shelters and isolated conductive roofs can allow intensification of the internal electric field, leading to the formation of dangerous streamers inside. Population of Colombian National Army is highly affectated by the lightning currents with a high annual average of injuries and deaths, due to their security activities carried out in open fields and faraway places.

Impedance circuit models of human body are useful for estimate currents to assess the risk of electrocution and ECG analyses, but lack in details about the actual paths that currents can follow inside the body and the effects on some tissues. Otherwise, 3D computational models use phantoms that consider most human tissues and organs with their electrical properties. With the results of these 3D models, it was theorized that lightning currents could have passed through a baby´s developing brain days before her birth, leaving long term disabilities and permanent sequelae, unlike other reported cases of lightning strikes in pregnant women that had no noticeable consequences.

Experiments conducted on samples of ECF using 8/20 μs and 10/350 μs waveform impulsive standard currents revealed three mechanisms of electrical conduction under the tested conditions. These mechanisms include ohmic conduction, which does not result in observable changes and damage; plasma conduction across horizontal gaps previously formed on the fabric surface; and plasma channels between both electrodes following previous tests.

Considering the experiments with 10 cm x 10 cm ECF samples using 8/20 μs lightning impulsive currents, resulting voltage vs. current plots suggest that the rip-stop ECF can carry a surface current density of up about 1 kA/cm as show an ohmic behavior where the voltage follows the current. Since the fabric samples subjected to 0.5 kA/cm did not exhibit significant alterations in the color of the surface, it can be concluded that they can safely conduct this current density. In single-impulse tests, horizontal scratches, perpendicular to the current flow were evidenced from about 10 kA, i.e., for current densities of 1 kA/cm, corresponding to around 20 J of energy dissipated. The applied energy does not seem to produce cumulative effects to consecutive tests since there would be a maximum limit of energy that could be dissipated in each single test. The morphological changes in color and loss of material over the fabric surface, appreciable as darkening and transversal scratches, are due to the phase change of the conductive material as it melts, boils, vaporizes, and bursts according to the applied energy. The 10/350 μs tests show agreement with these results considering however that this waveform has a higher energy.

A basic portable shelter model has been proposed using lightweight electroconductive fabrics (ECF) to divert the lightning currents outside the human body by providing an equipotential surface. The results of laboratory tests on electroconductive fabric samples and on the reduced model show that the proposed concept can protect human beings against ground currents and earth potential rise (EPR), showing that ECFs can withstand lightning-like currents. Thus, the risk caused by a nearby lightning strike can be considerably reduced by sheltering inside this type of tent, avoiding permanent injuries.

Through the analysis and development of the proposed personal portable lightning protection, some interesting questions arise. With the development of this research an interesting area of investigation has been revealed, with some related work developed even by other authors, showing the interest for lightweight lightning protection systems, and the uses and applications of electroconductive fabrics by the researchers working on lightning protection and high-voltage and high-current discharges.

5.2 Perspectives

1. Although textile science and materials science are very broad fields of research, it is important to integrate them more deeply into the development of future personal lightning protection systems and power applications of electroconductive fabrics. The development of fibers and weavings, and the use of alternative materials can improve characteristics of low electrical resistivity and high mechanical resistance. It is suggested to study other conductive materials, composites, and alloys that allow a high conductivity on the fabric such as the use of fibers from pure copper, alloying copper with palladium, silver, or steel. Additionally, to study the use of 2D nanocomposite films such as MXenes or buckypaper could reduce even more the surface resistivity of the electroconductive fabric giving a better performance of the fabrics used. The use of alternative fibers core materials other than polyesters could help to improve the mechanical strength and even the electrical properties of the fabrics.

2. High current densities such as those due to lightning currents can produce in conductive fabrics and other materials very fast phenomena such as phase change of metals, but also electromigration processes. As in the fields of microelectronics, power semiconductor devices, and integrated circuits, the study of electromigration in electroconductive fabrics can help to increase their ability to conduct high current impulses and, in general, electrical power. The current crowding effect is a field that still has much to be explored.

3. Further research is required in the application of electroconductive fabrics considering their surface resistance, demonstrated ability to conduct high currents, flexibility, easy to cut, availability, and other potential characteristics to be explored. Their use in electrical engineering such as in personal protection against high voltage, power shunt resistances, voltage dividers, surge protection, heating among many others must be considered.

4. The development and optimization of instrumentation for a test bench for impulsive currents over electroconductive fabrics and personal lightning protection is desirable. For several purposes it is necessary to have a current generator of 10/350 μs waveform with a least 10 kA peak and approximately 2 kJ. Despite a great challenge, research is suggested to carry out the implementation and testing of an impulse current generator with these characteristics. Additionally, the development, characterization, and calibration of Rogowski coils and current transformers to measure lightning-like currents and voltage dividers is recommended. Since measurement of floating voltages is also required, the study and implementation of differential probes for high voltage is suggested.

5. Applying the existing knowledge on explosive wires and the experience from this research, develop new tests to analyze electroconductive fabrics as explosive films.

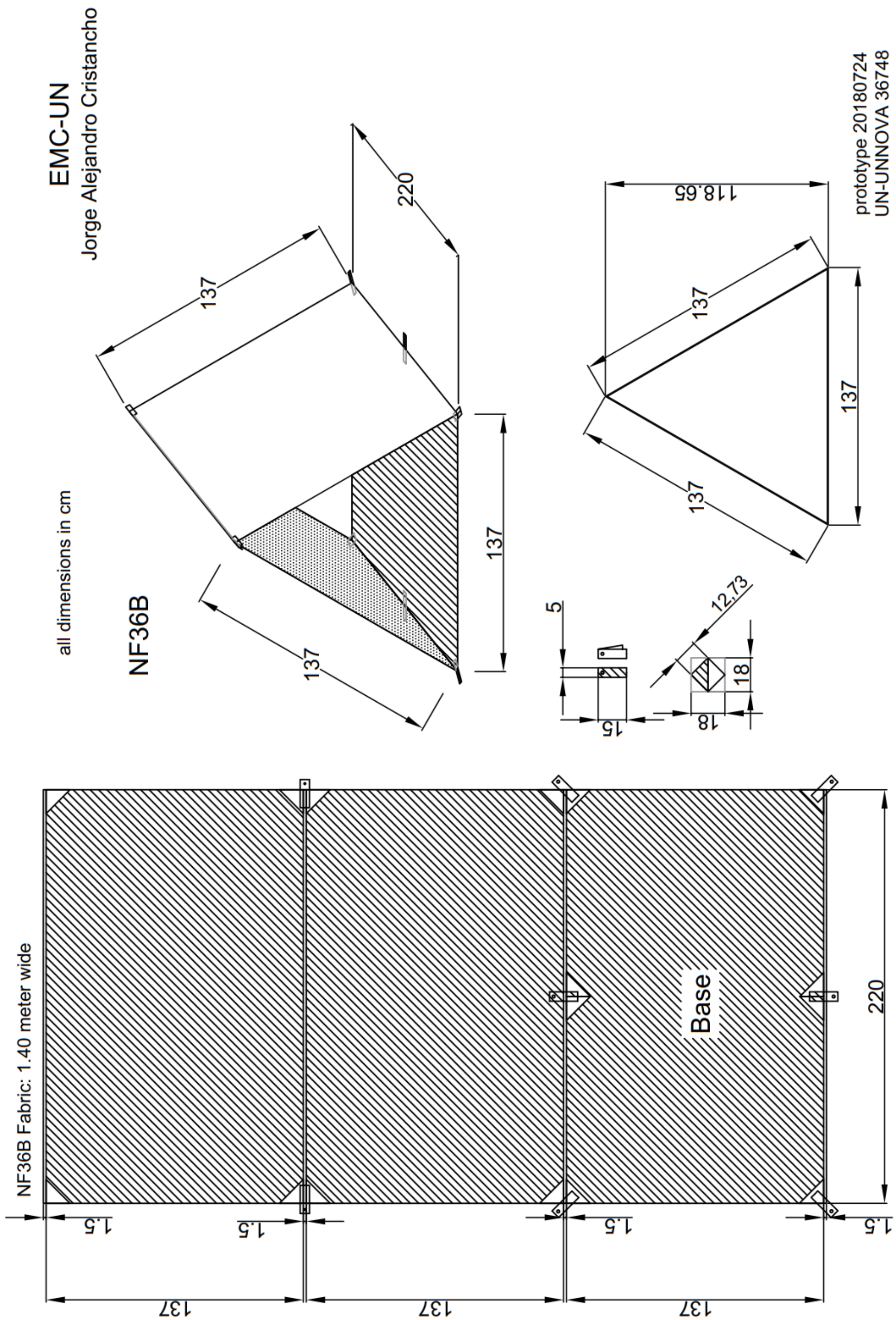
6. The study of the variation of the dynamic resistance against lightning-like currents for samples of electroconductive fabric and for the shelter model is proposed, taking into account that the resistance can vary as a function of several parameters such as: electromagnetic interference, temperature, humidity, pressure, mechanical stress, traction, and phase change of the conductive material.

7. It is desirable to test the full-scale model with lightning impulse currents of 10/350 μs waveform, but it would be even better under more realistic conditions, e.g., with rocket triggered lightnings. The respectful use of animal models inside the shelter during lightning testing should not be discarded.

8. The external support of institutions, organizations or companies that want to prevent injuries caused by lightning is important to continue with the starter of this research process. To give continuity to the agreements and projects that support the research of

our group in the development of portable lightning protection such as the one given by the EJC stimulates the continuity of the work done.

Appendix A. Dimensions of proposed model



Appendix B. Magnetic susceptibility of copper-nickel alloys at room temperature

The relative permeability of copper-nickel alloys can be estimated from magnetic susceptibility ($\chi_m = \mu_r - 1$).

TABLE I. *Magnetic susceptibility of copper-nickel alloys at room temperature.*

Percent Ni	$\chi \times 10^6$	Percent Ni	$\chi \times 10^6$ $H=1300$	$\chi \times 10^6$ $H=5700$
0.	−.14	40	2.90	2.90
0.1	−.08	50	10.83	10.83
0.5	−.02	54	18.3	18.3
1.0	+.02	55	20.5	20.5
2.0	.07	56	28.0	27.0
5.0	.14	58	58.0	51.6
10.0	.40	60	81.5	73.2
20.0	.82	65	2140.	710.
30.0	1.01	70	13300.0	—

[4] A. N. Guthrie and L. T. Bourland. Phys. Rev. **37**, 303 (1931).

Table taking from: E. H. Williams; Magnetic properties of copper-nickel alloys; august 15, 1931 physical review volume 38.

Appendix C. Presented and Published works

2015 International Symposium on Lightning Protection (XIII SIPDA), Balneário Camboriú, Brazil, 28th Sept. – 2nd Oct. 2015.

Nonfatal Lightning Injuries in Colombia: Case Reports

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***Abstract*— Lightning accidents involving several fatalities and injuries are reported every year in the world. Colombia, a country with a high keraunic level, reports frequently lightning fatalities involving several injury mechanisms. However, there are also some fortunate cases where the victims have survived without disabling traumas. Two nonfatal events in which lightning strikes persons are reported. In both cases it is observed that some metal objects such as necklaces or buckle belts saved the life and integrity of the victims. Moreover, both the relative localization and the comprehensive description of the cases scenarios involving visual consequences in the victim's skin are presented. The analysis of such accidents could be of interest to protect persons against indirect lightning currents.**

Keywords — nonfatal; lightning accidents; injures; Colombia

I. Introduction

Despite of reports indicating lightning strikes mortality rates of 30%, or as low as 5% to 10% [1], lightning is a real hazard during outdoor activities [2], mainly in places with increased risk by their relative position. As it can be observed in any world lightning map, the world largest lightning activity is located in the tropical zones. This information was recently ratified by the Global Lightning Activity Map -GLAM- processed by Nasa's Earth Observatory (EO) and published in march of 2015 [3]. The GLAM which is supported by the data collected from satellite observers such as those of NASA's Tropical Rainfall Measuring Mission (data from 1998 to 2013) and OrbView-1/Microlab satellite (data from 1995–2000) clearly shows the large lightning activity in the equatorial zone. Topography, time of the year and weather atmospheric conditions plays also important roles in the lightning activity. Therefore, some geographical areas are particularly more prone to lightning strikes than others [4-5].

Colombia, due to several factors is one of the countries in the world with the largest lightning density [5]. To this conspicuous lightning activity contributes its complex Andean mountain ranges, its location in the northwest part of South America between the Pacific and the Atlantic oceans and in the middle of equatorial zone. The large lightning figures related to Colombia during the years 2012 and 2013 mentioned in [3] and [5] could explain many with fatal and nonfatal lightning accidents. Just between 2003 and 2012 in almost one of two lightning accidents reported by the Direction of Integrity Preservation and Security of the Colombian Army (DIPSE) a soldier died [6].

In this scenario, two nonfatal lightning accidents caused by indirect lightning currents occurred in 2014 in rural areas of Colombia are analyzed and discussed. In both cases, two young and healthy soldiers were injured. Both soldiers were left without evident disabling conditions but their skin has shown evident burn marks. The first case (referred in the following as Case A), occurred in the "*Serranía de San Lucas*", department of Bolivar and the second case (referred as B) occurred in the "*Páramo de La Rusia*" located at 4.300 m above mean sea level in the department of Santander, as it is shown in Fig 1a.

II. Geographical Information

Both accidents took place in rural open areas with particular characteristics. Case A occurred in an ending extension of *Central Cordillera*, called *Serranía de San Lucas*, while case B occurred in the eastern mountain range, called *Cordillera Oriental* in a place known as *Complejo de Páramos Guantiva - La Rusia*. The approximate locations of both cases are shown in Fig. 1a. Also, the lightning flash rate is shown in Fig. 1b. Notice that the average atmospheric lightning activity is larger in case A than in case B.

1) Case A:

The *Serranía de San Lucas* is an isolated 110 km long mountain range with forested mountain massif of northern Colombia's *Departmento de Bolivar.* Mountains there rise from sea level to heights up to 2,600 m above sea level, being thus the northernmost part of Colombian Cordillera Central. It is part of the Magdalena-Urabá forests moist ecoregion. According to Köppen-Geiger climate classification shown in Fig. 1c [7], it corresponds to a transition area between the so called Tropical Savanna to the Tropical Monsoon Climate. The later goes inside of the Andean mountain range [http://www.thc-fc.org/PDF/SerraniaSanLucas.pdf].

Case A occurred about 500 m above sea level with an estimated hot and humid weather of 32 °C and (65 – 70) % relative humidity.

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Characterization of a Metallic Pearl-like Necklace stroked by lightning: *preliminary results*

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***Abstract*— Lightning accidents are frequent in Colombia. In the present investigation, a non-fatal accident is analyzed. For a better understanding of the accident, it was replicated in the laboratory a part of a reported case, in which a soldier, wearing a metallic identification pearl-like necklace, was struck by an indirect lightning current. Different 8/20 µs lightning impulse current amplitudes were applied to similar necklaces in order to determine its electrical parameters, such as dynamic resistance, the absorbed energy and the maximum withstand current. The preliminary experimental data obtained through the application of 8/20 lightning current impulses applied to necklaces is analyzed for a technical insight of the event.**

Keywords- Lightning accidents; Experimental simulation of lightning accidents in Colombia; current impulse in a metallic necklace.

I. Introduction

Colombia is one of the countries in the world with the largest lightning density [1], affirmation supported by several lightning maps indicating flashes per square kilometer per year as the ones shown in [2].

Events reported by the Direction of Integrity Preservation and Security of the Colombian Army (DIPSE), show statistics from 2003 to 2012, in which almost one of two lightning accidents results in mortal consequences [3]. One of these accidents with nonfatal results, identified as Case B in [3], is the object of present study. In Case B an indirect lightning current struck the metallic identification necklace weared by a Colombian soldier. The necklace was overheated and left burning marks around the neck's soldier as it is shown in Fig. 1.

The dynamic resistance of a similar pearl-like metallic necklace as the one wore by the victim during the accident, the maximum energy liberated by the lightning current and the highest lightning current that the necklace can withstand are investigated in the present research work.

II. Background

A lightning flash to ground is defined as an electrical discharge of atmospheric origin between cloud and ground, consisting of one or more strokes [4]. Most of lightning discharges are downward negative ground flashes, initiated by an electrical breakdown in the clouds, forming a column of charge and traveling from cloud to ground [5].

Figure 1. Injuries in the nape of the soldier caused by indirect lightning stroke [3]

A. Specific energy

The liberated energy by the impulse is proportional to the charge transported by the current i and it is defined as the time integral of the square of the lightning current i for the entire flash duration as:

$$\frac{W}{R} = \int i^2(t)dt. \quad (1)$$

B. Joule Heating

Joule heating makes reference to resistive heating. It describes the process where the energy of an electric current is transformed into heat when flows through a resistance [6]. Thus, the thermal energy liberated W by the current impulse is therefore the ohmic resistance of the lightning flash through the conductor (the necklace for this study) as follows,

$$W = R\int i^2(t)dt \quad (2)$$

III. Case Scenario

The scenario described in [3] and shown in Fig. 2, reports a Colombian soldier wearing an institutional stainless steel pearl-

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Determination of the Lightning Current from its Thermal Effects

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***Abstract*—Lightning accidents are random events whose electrical magnitudes are difficult to be measured or estimated. However, analyzing its consequences, some of its parameters, such as its possible trajectory to earth and current waveform and amplitude, can be reconstructed. This paper presents a methodology applied to estimate the lightning current based on both its thermal effects on a conducting material and on the burns left on a victim. The thermal effects are reconstructed by studying the skin burns left by a stainless steel pearl-like necklace wore by a soldier, which conducted an indirect lightning current. The current amplitude is estimated through Joule heating simulations in Comsol Multiphysics of a section of the metallic necklace. Analysis of results shows feasible lightning current amplitudes and waveforms, which could have impacted the victim. The methodology used here to reconstruct and to evaluate the lightning current could be of interest for further studies on understanding lightning accidents. Furthermore, the reconstructed lightning current amplitude could be a reference value for the future protection systems of population at risk in similar conditions.**

Keywords*- *Lightning; lightning accidents; lightning current; lightning heating

I. Introduction

Colombia is one of the countries with the largest lightning density in the world [1] mainly due to its geographical and climatic conditions. For this reason, a large number of lightning accidents are expected every year. Specifically, lightning accidents involving military population are very frequent in the country [2], leaving fatal and nonfatal victims depending on several local conditions [2-3]. Lightning accidents previously reported, in which metallic necklaces were involved [3], presents the accident scenarios but without analyzing the thermal effects of the lightning current on the victim's skin.

In this investigation, a methodology to estimate the lightning current starting from its thermal effects is proposed. This methodology is based on numerical simulations of Joule heating performed in Comsol Multiphysics and was applied to a particular case presented in [3], where a soldier in declined sitting posture on a military shelter was struck by lightning. Lightning hit the shelter structure passing through the high resistance sandbag wall, reaching the soldier personal identification metallic necklace (ID dog tag in ball chain) that he was wearing around his neck, entering by the nape zone. The current of the indirect lightning strike flowed throughout the soldier necklace, overheating and melting a part of it, and burning his nape skin as it can be seen in Fig. 1. To determine the lightning current amplitude, a reconstruction study based on the soldier necklace characteristics and on the estimation of the temperature which could burn the soldier skin was performed.

II. Background

Lightning discharges correspond to electrical discharges generated in the Earth's atmosphere due to several causes [4]. In the simulations performed in this paper, it is suggested that the current is of negative polarity as a consequence of a cloud-to-ground discharge, mainly because it has been established that the polarity ratio of lightning discharges is 10% positive and 90% negative [5]. Moreover, lightning current is defined as the current flowing at the point of strike and is characterized by different parameters, like time and amplitude [5]. The lightning current consequences depend on the previously mentioned two parameters and are directly related to the lightning current shape and its thermal effects on a conducting material, which in this case corresponds to the soldier necklace.

A. Lightning current expression

The lightning current impulse is defined in [5] as the time function presented in (1), where I is the peak current, k is the

Figure 1. Soldier's neck burn marks caused by the skin contact with the pearl-like spheres of his necklace heated by the lightning current.

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Analysis of two nonfatal lightning accidents in Colombia

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ABSTRACT

Several lightning accidents involving human fatalities and injuries are reported every year in Colombia. This work presents and discusses two non-fatal lightning accidents, where the victims survived without evident permanent disabling traumas. In both cases, it was observed that metallic objects such as necklaces or buckle belts worn by the victims were intercepted by the lightning current. These metallic objects could possibly be a pathway to keep the lightning current on the victim's skin surface. To understand the interaction of these metallic objects and the indirect lightning currents, both the visual consequences of the indirect lightning current on the victim's skin and a comprehensive description of the cases scenarios are presented.

1. Introduction

Some geographical areas in the world are particularly more prone to lightning activity than others. Local geographical and meteorological conditions play important roles in the lightning activity, such as topography, proximity to waterbodies, seasonality, seasonal variation, time of the year, mesoscale convective systems (MCS) or the interannual El Niño/Southern Oscillation (ENSO) among others [1–6].

Colombia, due to some of the mentioned factors, is one of the countries with critical zones of high flash density [2,4,7]. To this lightning activity contributes its complex Andean mountain ranges and its geographical position between the Pacific and Atlantic oceans in the northwestern of South America. Due its location in the middle of the equatorial zone that drives thunderstorms, Colombia is subjected to the ENSO phenomenon and MCS variations.

The large lightning activity linked to Colombia could explain many of the accidents with fatal and nonfatal consequences, as reported for 2012 and 2013 [8,2]. Sadly, between 2003 and 2012 almost one out of two lightning accidents reported by the Direction of Integrity Preservation and Security of the Colombian Army (DIPSE) left a dead soldier hit by lightning [8]. An analysis is required to determine the circumstances in which these events occur and to propose lightning protection measures to reduce accidents.

In this paper, two scenarios previously reported in Ref. [3], are described, in which two lightning accidents caused by indirect lightning currents occurred in backcountry areas of Colombia. Both cases, located in the maps shown in Fig. 1, relate scenarios where two soldiers were injured by lightning currents. These accidents did not produce evident disabling conditions but palpable burn marks in the victims' skins.

2. Geographical information

The accidents of the two soldiers that were struck by lightning during military activities were initially reported in Ref. [3] and are complemented here with more precise geographical and lightning data. These traumatic events occurred in mountainous zones of the northern part of Colombia, as it is explain as follows.

Case A occurred in a foothill extension of *Cordillera Central* (Colombian central mountain range) known as "*Serranía de San Lucas*" – on the Santa Rosa del Sur municipality, Department of Bolivar – placed at 1900 m above mean sea level, during a rainy night. The *Serranía de San Lucas* is an isolated long mountain range with forested mountain massif being thus the northernmost part of *Cordillera Central* in northern Colombia. It makes part of the Magdalena-Urabá forests moist ecoregion. As it is shown in Fig. 1(c), according to Köppen-Geiger climate classification, *Serranía San Lucas* corresponds to a transition area between the tropical monsoon climate to the tropical rainforest (equatorial climate). The

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III Encuentro Internacional de Tecnologías para el Desminado Humanitario – Medellín 2017

Protección contra rayos en actividades de desminado humanitario

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RESUMEN

Debido a la alta actividad de rayos a tierra en el territorio colombiano y particularmente en algunas zonas afectadas por la instalación de artefactos explosivos improvisados, es necesario dotar de un sistema de protección contra rayos a los equipos humanitarios que realizan el desminado tanto en tiempo de actividad como de descanso. En este trabajo se presenta cómo la actividad de rayos en el territorio colombiano puede afectar la salud e integridad de las personas que participan en las diferentes labores humanitarias a campo abierto en zonas donde la atención oportuna de emergencias en salud es de difícil o imposible acceso. En esta presentación se expone también el estudio del Grupo de Investigación EMC-UN en refugios para mitigar este riesgo catastrófico que sólo para el Ejército de Colombia cobra anualmente en promedio cerca de una víctima mortal y tres más afectados por mes, de acuerdo a estadísticas de la DIPSE (Dirección de Preservación de la Integridad y Seguridad del Ejército) para el periodo entre 2003 y 2013.

ANTECEDENTES

Colombia es uno de los países del mundo con más alta actividad de rayos. Cáceres, Antioquia con una densidad de 172 rayos por kilómetro cuadrado por año; El Tarra, Norte de Santander con 139 y Norcasia, Caldas con 124 están en el 4, 7 y 11 lugar de localidades con mayor actividad a nivel mundial para el periodo de 1998 a 2013. Además Colombia cuenta con 7 de los 10 lugares de más alta actividad de rayos en toda Suramérica. (Bulletin of the American Meteorological Society – November 2016, Vol 97, No 11). Los mapas de actividad de rayos como el mostrado en la Figura 1, muestran la distribución general de dicha actividad en el territorio colombiano para el periodo de 2012 a 2016 de datos suministrados por el sistema GLD360 de Vaisala.

Para Colombia se ha reportado que el índice de fatalidades por rayos entre los años 2000 y 2009 es de 76 muertes en promedio por año únicamente de los casos registrados en el DANE (Navarrete-Aldana, Cooper, Holle 2014 – Lightning fatalities in Colombia from 2000 to 2009) por lo cual la cifra seguramente es mucho más elevada. El mapa de la izquierda de la Figura 2 muestra la distribución por departamentos de las fatalidades reportadas causadas por rayos en el país para los años indicados.

Figura 1. Mapa de rayos para Colombia del periodo comprendido entre los años 2012 a 2016 donde se muestra el promedio de la densidad de todas las descargas por kilómetro cuadrado a partir de los datos del sistema GLD360 v2.0 de Vaisala con una resolución de 20 km x 20 km. La densidad de descargas eléctricas atmosféricas para varias zonas del país supera los 64 impactos a tierra por kilómetro cuadrado al año (Fuente: Vaisala / Ron Holle).

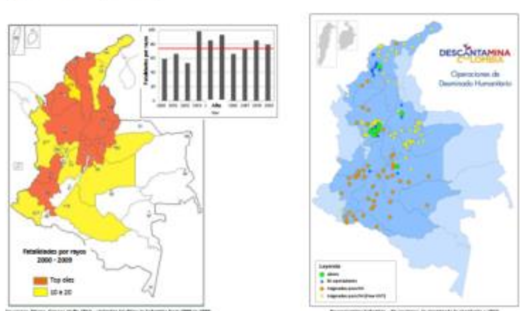

Figura 2. Izquierda: Mapa de fatalidades reportadas por rayos de 2000 a 2009 (Navarrete et al. 2014). Derecha: Mapa de departamentos y municipios con operaciones para el desminado humanitario a 2016 (www.accioncontraminas.gov.co)

MECANISMOS DE LESIONES POR RAYOS

En la literatura técnica se reportan seis tipos principales de mecanismos que causan lesiones al ser humano conocidos también como mecanismos de acople. Como se muestra en la Figura 3 estos mecanismos son: Impacto directo, potencial de contacto, descarga lateral, potencial de paso (o aumento de potencial de tierra), streamers ascendentes y lesiones por contusión. En un país desarrollado la frecuencia de fatalidades se distribuye entre el 50 al 55% en potencial de paso (*step potential* o *earth potential rise*), del 30 al 35% en descargas laterales (*side flashes*), del 10 al 15% en streamers ascendentes (*upward streamers*), del 3 al 5% en potencial de contacto (*contact potential*), del 3 al 5% en impactos directos (*direct strike*) y es indeterminado las ocurridas por lesiones por ondas de choque que provocan contusiones (*blunt injury*) como se indica en el diagrama de la derecha de la Figura 3.

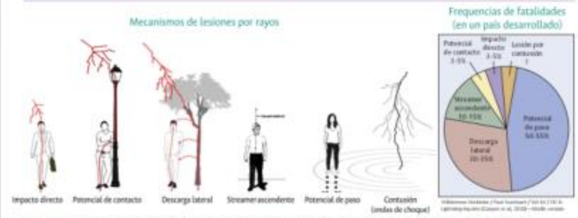

Figura 3. Mecanismos en que los rayos producen lesiones a personas y frecuencias de fatalidades

SITUACIÓN ACTUAL

Se muestra en la Figura 4 un caso común de instalaciones móviles en que el área carece de cualquier tipo de protecciones contra rayos. En situaciones que involucran las actividades a campo abierto, la permanencia transitoria o permanente de personas como el caso del desminado humanitario, es importante considerar varios factores como la hora, lugar, época del año, predicción del clima además de contar con refugios adecuados en caso de presentarse tormentas eléctricas cuando no pueden evitarse.

Figura 4. Izquierda: Base móvil sin un sistema de protección contra rayos. Derecha: Actividades a campo abierto de desminado humanitario (fuente: www.incarpas.com y www.rcnradio.com)

TRABAJO DEL GRUPO EMC-UN

Desde hace varios años el Grupo de Investigación en Compatibilidad Electromagnética de la Universidad Nacional de Colombia EMC-UN ha adelantado estudios para el desarrollo y aplicación de refugios fijos y portátiles que puedan mitigar el riesgo causado por la actividad de rayos en el país. Actualmente se cuenta con una solicitud de patente y se han realizado múltiples ensayos de laboratorio para analizar la funcionalidad y efectividad de las propuestas. La Figura 5 muestra una parte de estos trabajos.

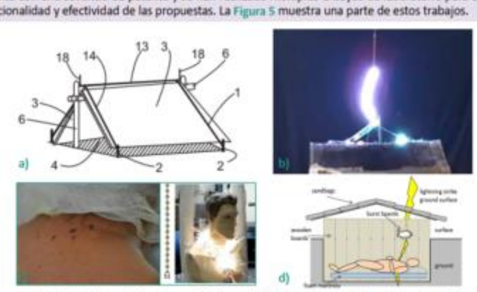

Figura 5. a) Solicitud de patente de un refugio portátil, b) pruebas en laboratorio de alta tensión sobre un modelo, c) estudio de caso de accidente, d) recreación y análisis de accidente en refugio excavado.

Conclusión

La alta actividad de rayos en el territorio colombiano y particularmente en algunas zonas afectadas por la instalación de artefactos explosivos improvisados exige la adopción de medidas de protección para mitigar el riesgo de afectación a los integrantes de los equipos humanitarios que realizan el desminado tanto en tiempo de actividad como de descanso. Se presenta el trabajo adelantado en el Grupo de Investigación EMC-UN de la Universidad Nacional de Colombia sobre el estudio de refugios para mitigar este riesgo catastrófico que en Colombia cobra en promedio más de 76 víctimas mortales al año.

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COLCIENCIAS

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Fatal Livestock Lightning Accident in Colombia

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***Abstract*— Lightning-caused accidents with multiple fatalities in livestock and other four-legged animal are informed by the media every year, frequently without any technical point of view, all around the world. This paper reports a lightning accident in *Los Llanos*, eastern plains region of Colombia, related to the death of a herd of 83 cattle occurred on May 2013. The relative localization and a description of the case scenario in which the cattle were sheltering from the rain on a scrub under some trees is presented. From the lightning data collected for the years 2012 to 2016, the incident area has an average lightning stroke density of 4 to 16 flashes per square kilometer. The analysis of this type of accidents would help to develop and improve protection systems for livestock against lightning currents and for insurance companies to assess livestock farming lightning risks and claim investigations.**

Keywords—Ligthning, livestock, 83 cattle killed, Colombia

I. Introduction

Worldwide lightning related fatalities on four-legged animals as cattle and other livestock reported by the media is not hard to found through any search engine. In April 2017 near Cabool, Missouri, a lightning strike kills 32 certified organic milk cows leaving economic losses estimated around USD$60.000 [1]. In August 2016, it was worldwide known the renowned case of more than 300 wild reindeer killed by lightning storm on a mountain plateau in central Norway in what was called an unusually large natural disaster [2]. These types of catastrophic events have social and economic implications, particularly in developing countries, as also wild life and environmental repercussions.

The main injury lightning mechanisms causing massive deaths, as in these accidents, is associated to Earth Potential Rise (EPR) or step potential, and also touch potential. These are the most common lightning injury hazard among four-legged animals and large groups [3], [4]. The body contact points of an animal with the ground or any type of conductive material could be entries to current associated to potential rise gradient in a lightning event. If the crossing current in the animal body is large enough, could affect vital internal organs endangering their life.

Scientific information about this matter is limited and there are not well enough documented cases reports of lightning related deaths on livestock [5]. Lightning-cause fatalities in cattle represents a serious problem to large and small dairy and beef farmers that perceive this as mysterious, sudden, and uncontrollable economic risk and an acute hazard to their finances and livelihood, particularly when they are not cover by some specialized livestock insurance, very frequent situation in developing countries.

In Colombia media spread the news about lightning-cause deaths in livestock without further depth information when the figures are remarkable. This paper reports a case, and do a retrospective look analysis, related to the death of 83 bulls due to a lightning strike on May 2013 in the *Los Llanos*, on the Colombian side of eastern plains of Orinoco river basin. This case was reported by the media as "A lightning flash burned 83 cattle in Hato Corozal, Casanare" [6], [7]. Media reports that the herd of cattle was scorch by lightning because of the burning smell. The death of the animals supposed a serious risk to health in the area from what the authorities decided to incinerate the carcasses of the livestock to minimize rotting odors among other environmental consequences that could be generated by the decomposition of the bodies.

II. Case Report

A. Location

The lightning accident resulting in the death of 83 cattle take place in the Hato Corozal municipality of the Department of Casanare, Colombia on 6 May 2013, in a rainy afternoon. A lightning hit the farm *El Chaparro* in the location at coordinates 6°10'18.13" N, 71°36'19.74" W, 250 m above mean sea level, 17 km from the Hato Corozal downtown, close to the Casanare River on the natural region of *Los Llanos*, tropical grassland plains in east Colombia and central Venezuela. Casanare River is a tributary of Meta River that flows into Orinoco in a region characterized by two well-defined seasons: one dry season (December to February) and one rainy season (March to November). Climate of Hato Corozal municipality is considered to be "Am" – Tropical Monsoon Climate [8], [9] according to the Köppen-Geiger climate classification. The short dry season has little effect on the overall climate and the long rainy season counts for annual rainfall precipitation averages 2761 mm and modules the temperature averages to 26 °C. Fig. 1 shows the location of the accident place in a Colombia-Venezuela map in northwestern South America. Casanare area had normal precipitations on May 6th 2013 with a daily value about 70 mm for the date [10].

In spite of lightning maps reveal a relatively low ground flash density rates on the accident area from 4 to 16 flashes per square kilometer when compared to other hotspots in Colombia (that could surpass 64 flashes per square kilometer per year)

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Lightning fatalities in the livestock industry in Colombia: Eastern plains region case

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***Abstract*— In this paper we present a statistical study of lightning fatalities which are present in the Colombian eastern plains region known as *Los Llanos Orientales*. The main economic activity of this region is the cattle farming and has presented several events of multiple deaths of cattle by lightning.**

***Keywords*— Livestock, lightning, fatalities, Colombia, relative lightning death indicator**

I. Introduction

On May 6, 2013 Colombian local [1] and national [2] media reported that 83 cattle were killed by lightning. Similarly, in 2016 the local media reported the death of 30 cattle [3]. The two cases occurred in the municipality Hato Corozal at the Department of Casanare, located in the Colombians eastern plains region. For decades livestock farming has been one of the main economic activities of the region. FEDEGAN *(Federación Colombiana de Ganaderos)*, - Colombian Federation of Livestock farmers, informs that up today there are no statistics on accidents or fatalities caused by lightning in this sector of the economy.

Colombia, which records 23.7 million heads of cattle, is the fifth livestock producer in America after Brazil (185 million head), USA (91.5 million head), Argentina (47.5 million head) and Mexico (32.9 million head) [4]. It is estimated that there are 1053 million heads of cattle in the world.

In Colombia, extensive ranching predominates, from 2 to 3 animals per hectare [5]. The main objective of the present paper is to present a first approach of the fatalities and damages caused by lightning in the Colombian livestock industry of the Eastern Plains Region, called *Llanos Orientales*, which is indicated in Fig. 1.

II. Lightning Accidents and Livestock

All over the world cattle fatalities are mentioned. Table 1 shows the most relevant events involving more than 10 bovine fatalities. Events with photographic records and reported in different media are the only included in Table 1. Events reported in Table I occurred mainly under a tree, close to a cattle barbed-wire fence or in the salt shaker. The pictures in Fig.2 show some examples of some of the multiple fatalities mentioned in Table 1.

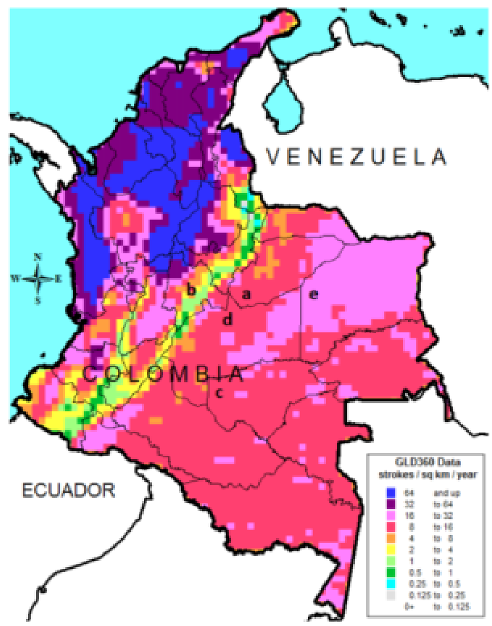

Fig. 1. Lightning stroke density map with a 20 km grid from GLD360 v2.0 of Vaisala dataset for 2012 to 2016 (source: Adapted from Holle R., personal communication, June 8, 2016 [6]). The literals indicate the location Eastern Plains Region or Llanos Orientales (department's a- Casanare, b- Cundinamarca, c- Guaviare, d- Meta and e-Vichada). Notice the important lightning activity in this area with a density between 4 to 16 strokes in a 20 km grid.

TABLE I. Events With 10 Or More Cattle Fatalities Due To Lightning

Date of event	Location	Cattle Death	Description
30/07/2008	Germany [7]	11	Under a tree
00/09/2008	Uganda [8]	53	Under a tree
23/10/2008	Uruguay [9]	52	Near a Fence
14/06/2009	Scotland [10]	16	Under a tree
16/08/2009	Brazil [11]	21	Near a Fence

High Current Tests over Conductive Fabrics

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***Abstract*— Lightning, as a powerful natural phenomenon, is dangerous for living beings, equipment, structures, and buildings. The protection principle against lightning currents is to divert and conduct them safely into ground. Therefore, materials and components of lightning protection systems (LPS) must be able to bear lightning currents on the order of tens of kiloamperes. On the search of light materials for LPS, we performed several laboratory tests with high-current lightning-type impulses over some different types of commercial conductive fabrics. The samples used as object under test (OUT) were pieces of 10 cm x 10 cm from four different types of conductive fabrics, including rip-stop, plain-weave and non-woven commercial ones. The OUTs were subject to four 4/10 µs impulsive currents up to 20 kA generated by an Impulse Current Generator. Were taken images of before and after tests and both current and voltage on the OUTs were recorded. Moreover, Scanning Electron Microscope inspections were performed after the tests, to understand some particular patterns presented on the fabric surfaces. A rip-stop type of conductive textile looks that withstands better the four impulses applied. The results of carried out tests suggest that is possible to use some conductive fabrics as part of a LPS, particularly in lightweight and portable applications required in outdoor conditions, such as in the cases of mobile shelters and tents.**

Keywords*— *conductive fabrics, high-current tests, lightweight lightning protection system, shelter

I. INTRODUCTION

Consequences of lightning strikes on living beings, equipment, structures, and buildings can be severe depending on several factors, such as the struck object, point of impact, lightning parameters, current path, or soil conductivity. As the lightning activity in the world has an uneven distribution, there are places more prone to lightning strikes than others, as shown on lightning maps. Places with high annual frequency of lightning activity have more accident occurrence probability related to this phenomenon. The 100 places of the world with the highest lightning activity present a density that ranges from 83,45 to 232,52 flashes per square kilometer [1]. Colombia has 7 of the top 10 places of South America with highest lightning activity ranging from 77,02 to 172,29 flashes per square kilometer with several related accidents. Just for the Colombian Army, lightning accidents account for 72 fatalities and 210 injured people in 8 years between 2003 and 2012 [2].

Lightning protection systems (LPS) are used to protect living beings, structures, and equipment against lightning effects. LPS are intended to intercept, conduct and disperse safely into the ground the lightning currents [3, 4]. Since lightning currents could reach tens of kiloamperes, materials and components of LPS should be able to bear effectively these currents. Particularly, the standard IEC62305 presents methodologies to guarantee risk reduction in order to avoid physical damage and life hazards. IEC62305-3 gives guidance in the use of materials and components, which are considerably heavy in most of cases. However, the conditions imposed by outdoor activities on remote and isolated places, constrain the use of weighty materials and equipment, necessary to an adequate LPS. So, most outdoor people remain frequently exposed to a catastrophic risk. In order to protect mobile campsites in places with lightning strike risk are required lightweight LPSs, desirable in a quick and easy to use form.

On the quest of lightweight materials to use as part of LPS different materials should be considered and assessed. It is also necessary to analyze existing data and carry out electrical tests to found what the best ones. For instance, nonfatal lightning accidents reported reveals the possibility of some light metallic elements could help to preserve the people's lives [5].

Some technical fabrics with high electrical conductivity have interesting potential to apply in the personal protection against weak and strong electromagnetic fields. These materials are lightweight surfaces (sheets), easy to handle and with low resistivity. Most of the conductive textiles are intended for shielding low power electromagnetic fields such as non-ionizing low and high frequency radiations. In this work we are assessing the behavior of some conductive fabric samples tested under 4/10 µs impulsive high currents through high-voltage laboratory tests and microscopy observations.

II. CONDUCTIVE FABRICS

A. Brief Overview

The most common structure of the fabrics are woven or nonwovens ones [6]. Woven fabrics are formed weaving threads of several yarns made of individual fibers. On the other hand, nonwoven fabrics have a structure made by bonding short and long fibers together, using mechanical, chemical, thermal or solvent means, and combinations thereof. The final application of each fabric type depends on both structural design and properties of constituent yarns and fibers [7].

A conductive fabric can be considered a special type of technical textile with the ability of conduct electrical currents because to their low electrical resistivity. The group Messe Frankfurt through the Techtextil Exhibition Trade Fair has 12 application areas of technical textiles [8, 9], fitting in the "Protech" classification the developments in personal and

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Thermal Simulation of a Conductive Fabric Sheet Subjected to a Lightning-like Current

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***Abstract*— A sample of electroconductive fabric subjected to a lightning-like current impulse is analyzed in this contribution. A multiphysics simulation is used to calculate the temperature distribution produced by a lightning-like current flowing through the material sample. A decoupled, electromagnetic (EM) and thermal, simulation was conducted for the analysis and is explained in the paper. The scaling factor calculation to represent the energy presented during current impulse tests is also detailed. Numerical results present patterns that agree with experimental tests reported in the literature and represent an additional tool for the phenomena insight.**

Keywords—Conductive fabric, electromagnetic simulation, impulse current, lightning, thermal simulation.

I. Introduction

Conductive fabrics have shown promising performance for different applications such as electromagnetic shielding, antennas, sensors, water treatment, and more recently lightning protection [1, 2]. Preliminary tests, in which different kinds of conductive fabrics are tested against lightning-like current impulses [1], show that the textiles can withstand high intense current impulses and provide a conductive path for lightning currents. However, the thermal stress produced in the electroconductive fabric materials during this kind of tests have not been studied in depth.

In this paper, a multiphysics simulation, including electromagnetic and thermal phenomena, is conducted in order to calculate and analyze the temperature produced in a sample of conductive fabric subjected to a high intensity current impulse.

II. Simulation Setup

The characteristics of the excitation signal and the samples under test are the same as the reported ones in previews experimental results [2].

A decoupled, electromagnetic (EM) and thermal, simulation was conducted for the analysis. The general steps for the simulation can be summarized as follows. First, the electromagnetic (EM) simulation is conducted. Then, power losses are calculated from the EM simulation. These losses are the source of the thermal simulation. Finally, thermal simulation is conducted and temperature distribution is obtained.

A. Conductive Fabric Samples

The selected samples of electroconductive fabrics tested in [2] are pieces of 10 cm x 10 cm of non-woven conductive fabrics. The main electrical characteristics of the samples are presented in Table I. Physical characteristics presented in the table are based in the manufacturer data. Simulation parameters, also included in the table, are based on experimental results reported in [2] and typical properties of the fabric's conductive materials.

B. Excitation Signal

The excitation signal used in [2] is a current impulse of 13,7 kA, 4/10 µs. The energy reported for this signal was with a time to half value of 10 µs. Since the used thermal simulator only imports power losses from EM simulation in frequency domain at one frequency and the excitation signal in the experimental tests is a pulse, different excitation signals were used in EM and thermal simulations. For the EM simulation, the excitation signal corresponds to a current signal injected in the sample. A Gaussian excitation covering the frequencies up to 20 MHz was used.

For the thermal simulation setup, a square pulsed excitation was used. The source in the thermal simulation corresponds to the imported losses from the EM simulation. For this reason, the average power of the pulse signal in the thermal simulations has to be calculated. The average power of a square pulse excitation can be estimated as:

$$P_{ave} = U/\tau, \qquad (1)$$

where U is the delivered energy and τ is the pulse duration. In this case, it is assumed that the power is produced by a continuous wave signal. Therefore, if the power P_{ave} is produced by a continuous wave signal, the required current to obtain that power can be obtained from the power dissipated in a resistance. In our case, the conductive fabric is the resistance that dissipate this power into heat,

$$P_{ave} = \frac{I_{peak}^2}{2} R. \qquad (2)$$

From (1) and (2), the equivalent current to produce the same energy used in the impulsive tests can be calculated. Using $U = 104$ J, $\tau = 10\ \mu s$, and $R = 0.03\ \Omega$, a peak current of $I_{peak} = 26.3$ kA is obtained. This result provides the scaling factor used in the thermal simulation for the losses 26.3×10^3, which corresponds to the ratio between the desired peak current and the peak current used in the EM simulation that in this case was 1 A.

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Model for the Estimation of Partial Burst of Ripstop Electro-Conductive Fabrics

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Abstract

This paper presents the analysis of high current impulsive tests performed on electro-conductive fabrics. A ripstop conductive fabric is tested against 5.4 kA and 9.0 kA 8/20 μs lightning currents. An equivalent circuit is used to represent the conductive interwoven yarns and the contact resistance between them. Using the proposed circuit and calculating the Specific Action applied at the woven sections and at the contact points, the change of phase and the loss of material on the conductive layer is described. Results show that the Specific Action can be used to estimate determined effects in materials as function of the excitation current signal.

1 Introduction

Conductive fabrics are components interesting for diverse applications due to their remarkable characteristics such as light weight, high flexibility, impermeability, conductivity, and durability. Some applications include conveying electrical signals, textile-based sensors, electromagnetic interference shielding, and heating textiles [1]. Different tests have been conducted to evaluate the applicability of conductive fabrics as part of a lightning protection systems (LPS) [2, 3]. Particularly, experimental tests reported in [2, 3] show that high intensity impulse currents produce partial melting of the fabric's external conductive layer but the conductive behavior is still maintained at certain levels of current. Therefore, preliminary results suggest that conductive fabrics can be used as part of portable LPS [2].

Electro-conductive properties of textiles have been studied from experimental tests. Anisotropy resistance of woven or knitted was reported in [1] and change of resistance of woven and non-woven fabrics due to lightning-type current tests has been reported in [3]. These kind of tests indicate effects of macroscopic parameters, such as surface roughness [1] or sheet resistance [3], on conductive properties. For some analysis, however, such as melting or burst estimation, parameters to describe particular microscopic details of the fabric structure are required.

Scanning electronic microscope (SEM) micrographs of conductive fabrics obtained after lightning impulse tests show the loss of material due to melting and sublimation of the conductive layer [3]. A key parameter to define the application and limits of materials conducting high current is the energy density.

We propose a different mechanism of analysis which takes into consideration the Specific Action, [4] as an additional parameter. This has been used in the literature in order to determine the resistivity of exploding wires carrying high impulsive currents. Therefore, using Specific Action we'll describe the performance and limits of ripstop conductive fabrics subjected to impulsive currents.

2 Specific Action

The Specific Action is a parameter proposed for the analysis and estimation of the performance of conductors subjected to high intense impulsive currents, such as in the study of exploding wires. Specific Action g is defined as [4]

$$g = \int j(t)^2 dt \qquad (1)$$

where j is the current density in the conductive material. In a wire or a conductive sheet, g can be calculated as

$$g = \frac{1}{A^2} \int I(t)^2 dt \qquad (2)$$

where I is the impulsive current and A is the initial cross-section area of the conductive material. The specific action is related with the energy density by [4]

$$e = \int \rho dg \qquad (3)$$

where ρ is the material resistivity, dg is the differential of the Specific Action.

As the energy density injected rises, the conductor resistance increases due to Joule's effect and due to loss of area as the material melts and vaporizes. The value of the Specific Action determines these phase transitions and is preferred to the energy density in this analysis since it is not dependent on the conductor resistivity, which is a function of the temperature and, as a result, on the energy density [4].

Conductive fabrics integrate different structures and materials to provide specific mechanical and electrical

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Lightning impulse current tests on some electroconductive fabrics

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Abstract: On the search of lightweight lightning protection materials that can be used as part of lightning protection systems (LPS), we investigate some types of electroconductive fabrics by applying several lightning impulse currents in laboratory. Samples of four commercially available electroconductive textiles were analyzed: two rip-stop, a plain-weave, a nonwoven, and additionally a carbon-impregnated polymeric film. Under laboratory conditions, each sample was subjected to several lengthwise subsequent lightning-like currents of 8/20 µs waveform, recording both voltage and current signals. Optical and scanning electron microscope observations were performed after tests, revealing some patterns or morphological changes on the fabric surface. Despite these changes, the investigated conductive textiles withstand the several lightning impulse currents applied. Results suggest that some conductive fabrics could be used in personal mobile shelters, to protect human beings against the earth's potential rise caused by a close lightning discharge.

Keywords: Lightning protection, portable lightning protection system, conductive fabrics, high-current tests, tents, electroconductive textiles

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