Action Volume Ratio - A method to classify the danger of lightning in any given volume

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Declaration

I declare that this thesis is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed this 27th day of September 2014

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Abstract

The annual number of injuries and fatalities from lightning has, over the last century, been on a steady decline. This is primarily due to urbanisation and movement away from agriculturally intensive activities. In countries with a high urban population, the incidence of lightning fatalities is below 1 death per million people per year. However, in countries with a larger rural population, this rate is significantly higher, ranging between 8 and 15 deaths per million people per year. There has been a large drive towards educating the general public about the dangers of lightning and methods to avoid being in a dangerous situation. However, fatal lightning events still occur on a regular basis.

There are currently no methods to determine the risk of lightning to living beings in open spaces. The international standard (IEC 62305-2) provides a method for the assessment of risk to living beings within a structure, and up to three metres outside of it. Considering that the majority of deaths by lightning occur outdoors, a method of determining these risks is necessary.

The Action Volume Ratio (AVR) is proposed as a new method for the analysis of the danger of lightning in any volume. It considers the dangers of all lightning injury mechanisms in relation to the objects in the space, which are assumed to be the preferential points of strike. A union of the dangerous volumes is then formed, and a ratio to the total volume is created. The AVR uses accepted electrical engineering equations to determine the dangerous areas, and places no reliance on probability theory, which can, in many cases, skew the results of a lightning risk analysis process. The AVR can be combined with lightning ground flash density data to indicate the incidence and frequency of dangerous events within a given volume.

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"*Warm-blooded, passionate, inherently social beings though we think we are, humans are presented in this context as hedonic calculators calmly seeking to pursue private interests. We are said to be risk-averse, but, alas, so inefficient in handling information that we are unintentional risk-takers; basically we are fools*" - Douglas 1992

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List of Symbols and Operators

The principal symbols and operators used in this thesis are summarised below. The units are shown in square brackets and the first equation where the symbol is used is given.

d	Striking distance [m], *Equation (3.1)*
I_p	Return stroke peak current [kA], *Equation (3.1)*
A, b	Constants, *Equation (3.1)*
H	Height of object [m], *Equation (3.2)*
N_f	Ground flash density [$km^2/year$], *Equation (3.2)*
A_d	Collection area of the object [km^2], *Equation (3.3)*
N_g	Lightning ground flash density [flashes/km^2/year], *Equation (3.3)*
L	Length [m], *Equation (3.4)*
W	Width [m], *Equation (3.4)*
H	Height [m], *Equation (3.4)*
K	0.065 to 0.165 $\mathrm{As}^{-0.5}$, according to weight, *Equation (4.1)*
t	Shock duration [s], *Equation (4.1)*
I_{ref}	The body current from the left hand to the feet [A], *Equation (4.2)*
I_h	The body current for a chosen current path [A], *Equation (4.2)*

F	The heart-current factor, *Equation (4.2)*
R_{gr}	Ground resistance of system [Ω], *Equation (4.3)*
$I(t)$	Lightning current [kA], *Equation (4.3)*
L	Inductance of the down conductor [H], *Equation (4.3)*
h	Height above the ground [m], *Equation (4.3)*
ρ	Earth resistivity [$\Omega\, m$], *Equation (4.4)*
I	Peak current [kA], *Equation (4.4)*
a, b	Distance from point of strike [m], *Equation (4.4)*
R_e	Single foot resistance [Ω], *Equation (4.5)*
b	Radius of a flat plate representing one foot [m], *Equation (4.5)*
A	Event, *Equation (5.1)*
C	Consequence, *Equation (5.1)*
U	Uncertainties not captured by P, *Equation (5.1)*
P	Knowledge based probabilities, *Equation (5.1)*
K	Background knowledge upon which U and P are based, *Equation (5.1)*
P_f	Relative frequency-interpreted probability, *Equation (5.2)*
R	The value of probable average annual loss [yr^{-1}], *Equation (5.4)*
N	The number of dangerous events per annum, *Equation (5.4)*
P	The probability of damage to a structure, *Equation (5.4)*
L	The consequent loss, *Equation (5.4)*
I_{mp}	Median peak return stroke current [kA], *Equation (6.3)*
Z_g	Earth impedance [$\rho\,$m], *Equation (6.3)*

Z_b	Impedance of the living being in the space [Ω], *Equation (6.3)*
l_{step}	Step length [m], *Equation (6.3)*
$\mathrm{A}_{mech\,j}$	Total area/volume defined per injury mechanism per inanimate object in a volume, *Equation (6.4)*
A_{Ω}	Total area/volume being assessed, *Equation (6.4)*

Chapter 1

Introduction

"When lightning roars, go indoors" is a slogan that was developed for lightning education. Simple methods to determine the dangers of an approaching storm, like the 30/30 rule are also taught. However, each year there are still a significant number of injuries and fatalities that occur as a result of lightning. Every alternate year, the International Conference on Lightning Protection is held, at which work is presented covering a wide variety of lightning related research topics. These conferences started in 1951 with a small European contingent. The present day conference consists of a few hundred researchers from around the world. This research has aided in the development of international standards in the areas of lightning protection and risk management. Within the history of the conferences, no work has been performed in considering the risks of lightning in open spaces. This may be because the risk is considered to be so obvious that this would seem unnecessary, however, lightning deaths still occur. Therefore, a risk analysis process needs to be established that is accessible to both experts and lay people alike.

There are numerous studies and standards defining the interaction of lightning and structures (IEC (2007*b*,*d*); D'Alessandro (2003); Cooray & Becerra (2010)) . Dalziel & Lee (1968) and Kitagawa *et al.* (1973), both performed extensive work to gain an understanding of the electrical characteristics of the body. This has provided insight into some of the parameters that may be responsible for fatalities of living beings from a multitude of electrical sources. Much of this work has been included in standards such as IEC 60479-1,2,3,4 (IEC (2006, 2007*a*, 1998, 2005*b*)). There are however, still many uncertainties as to the interactions between a living being and lightning transients, therefore, further work is still required. Ethical and moral issues, however, limit the amount of work that can be performed in this direction (Cooray *et al.* (2007*a*)). Therefore, there are still a significant number of unanswered questions relating to these interactions, thus hampering the ability to determine the exact parameters that result in a fatality.

The term ‘risk’, was originally attributed to nautical voyages, and their associated dangers. In today’s modern society, it enters every facet of life, but the meaning or calculation of risks is questionable. Extensive lightning risk assessments are often complicated and, therefore, risk analyses are often simplified and, as such, do not provide the necessary information in the results. The weighting factors are presented for use, but the origins and, therefore, applicability to the analysis process are concerning (Metwally & Heidler (2007)), as is the potential to skew the final results and therefore mask the actual risks.

> *“The risk evaluation is too complicated to use in all cases or in the standardization; therefore it must be adapted to the everyday routine. It is not a feasible way to replace the exact calculation with simple formulas and arbitrary factors and to call the result a risk. This procedure is not exact enough for important cases, but it is not simple enough for everyday routine.”* - Horváth (2004)

The current lightning risk management standard, IEC 62305-2 (IEC (2007*c*)), provides equations to determine four different risk types; the loss of life, services, cultural heritage and economic value. The method of analysis for the risk of loss of life, only considers a structure and up to 3 metres outside it. There are currently no methods to determine the risk of lightning in open spaces. However, the majority of lightning injuries and fatalities occur in outdoor environments. Through urbanisation and education, the number of incidents have decreased, however, there are many scenarios whereby basic lightning protection measures being in place would have reduced the number of injuries or fatalities.

1.1 Hypothesis and contribution

A method for determining the dangers of lightning in any volume is proposed. This method removes the concepts of probability and loss from any scenario, therefore it should not be considered as a risk analysis method. The concept of weighting factors to identify a common trend is not possible, as there are too many variables that all have an influence on the outcome of an event. The method is based on sound electrical engineering principles, used to determine a ratio of the dangerous area to the total area under investigation. This method can be combined with lightning ground flash density data to provide incident and frequency values associated with expected dangerous events in a space.

The contribution of this work is the following:

- The Action Volume Ratio (AVR) provides a method to describe the danger associated with lightning in any volume.
- The application of the AVR includes:
  - Inside structures
  - Boundary areas, between structures and outdoor environments, greater than 3 metres from the structure.
  - In any open space.
- The results determined by the AVR can be combined with lightning ground flash density data, to provide an incidence and frequency of events within the space being assessed.
- The solution is not limited to lightning fatalities, but holds for injuries as well.
- The AVR method can be expanded to incorporate new research relating to lightning injury mechanisms.
- The AVR method can be presented to lay people in graphical format, providing a clear representation of the dangers associated with lightning in a particular space.

1.2 Structure

This thesis is divided into two main sections; the first component consists of *Chapters 2, 3, 4*, and *5*, which present current knowledge and understanding in the context of lightning, living beings and the interactions that occur. The second section, consisting of *Chapters 6, 7,* and *8*, details the development of the Action Volume Ratio method. The AVR is then used to analyse two case studies of lightning incidents which resulted in the deaths of living beings.

There are two appendices, which provide information into lightning case studies from a number of different research areas. The current lightning risk analysis methods as described by IEC 62305-2 are presented, and the application in assessing various structures is performed.

The chapters in this thesis are presented as follows:

Chapter 2 - Lightning mortality and morbidity: This chapter presents lightning death and injury statistics from around the world. The data provides insight into the location, gender and age distribution of lightning fatalities and injuries. The collection of this sort of data has, for many years, been reliant on press and general media sources; however, more countries are now creating dedicated records of lightning fatalities.

Chapter 3 - Physical world parameters during a lightning strike: In this chapter, general lightning parameters are presented. Three areas are presented which include the latest South African lightning ground flash density data. The parameters of the electrical properties of a lightning stroke are discussed; these affect the way lightning interacts with different ground-based objects. In addition, general information regarding the interaction of a lightning stroke with the ground is presented. Finally, different methods used in determining the preferential point of strike are discussed. These methods also provide a means of determining the areas afforded protection from lightning by a tall structure or object.

Chapter 4 - Lightning and living beings: In this chapter, three sections are considered. Firstly, the electrical properties as well as an equivalent circuit model of the human body are presented. This includes descriptions of cells and their surrounding fluids and therefore how electrical current may interact with tissue. Secondly, the mechanisms of lightning injuries are described, as well as what damage electrical current passing through the body may cause. Finally, a discussion regarding a number of lightning incidents that have been published is presented. In many cases, large groups have been involved, which result in both fatalities and injuries.

Chapter 5 - Risk: In this chapter, the concepts of risk are presented. Traditional risk assessment methods, such as the realist perspective, are considered alongside those of the sociocultural perspective. Lupton (1999) describes the fact that risk has become an increasingly pervasive concept in modern society. Every action or decision has some associated risk attached. Means of quantifying the risk can be difficult, and the results of risk assessments are often unclear and have little meaning. International standards provide the best available means of determining the risk associated with lightning to living beings. The current lightning risk standards are discussed and observations in their application are presented.

Chapter 6 - Action Volume Ratio - AVR: In this chapter, the Action Volume Ratio (AVR), is proposed as a new method for determining the danger of lightning to living beings for any volume. This method applies the engineering principles used in understanding how lightning interacts with grounded objects, to determine the potential dangerous areas for living beings in both structures and open spaces. The AVR method can be combined with lightning ground flash density data to provide incidence and frequency values. It can also be presented numerically and visually, which provides a useful tool to present the dangers associated with lightning to engineers and lay people alike. The previous chapter explored conventional risk analysis methods, however, it will be shown that these methods have limited significance for defining risk in outdoor environments. The Median Lethal Limit (MLL) was first developed through forensic investigations of lightning scenes, which will be discussed further in *Chapter 7*, to define a two dimensional lightning danger representation for any given outdoor environment. This method is further expanded to provide a means of defining the danger of lightning to living beings in any given volume (AVR), and will be shown in a number of examples.

Chapter 7 - Case study: Critically endangered Kenyan Mountain Bongos (*Tragelaphus euryverus isaaci*): In this chapter, an animal enclosure in the National Zoological Gardens (NZG), in Pretoria, South Africa, is assessed using the Action Volume Ratio (AVR). The assessment is considered only for the median peak current value of a negative lightning return stroke, as per the probability distribution function, as defined by the IEC. By the definition in *Chapter 6, Page 78*, this case study will use the Median Lethal Limit (MLL) for the analysis. This is because the space being assessed is effectively a two dimensional system, where the space is limited to that area of the enclosure where the animals are found. The significance of this assessment is the fact that it highlights the dangerous areas in the enclosure. The interest in this case is that the animals were Kenyan Mountain Bongos (*Tragelaphus euryverus isaaci*), which are a critically endangered species.

Chapter 8 - Case study: 22 cattle killed by lightning: In this chapter, the AVR method is applied to a cattle enclosure, located on a farm in the Mpumalanga province, South Africa. A lightning strike resulted in the deaths of 22 cattle. A transmission line crosses the enclosure, which provides a certain amount of protection, and the case study provides an opportunity to present how different objects in the environment are considered when calculating the AVR. The concepts of the collection area and rolling sphere model are used in the analysis.

Chapter 9 - Conclusion: The Action Volume Ratio (AVR) is a new method that describes the dangers associated with a lightning strike within any volume. This method uses accepted engineering principles to determine the dangers associated with different lightning injury mechanisms within the volume being assessed. The union of the dangerous areas is summed and divided by the total volume to determine the AVR. This method can be used in both a technical assessment, as well as an aid in educating lay people about the dangers of lightning within a given volume.

Appendix A - Reported lightning injuries: Lightning statistics and information relating to incidents have, in the past, generally only been made available through the press. Eye witness reports are, at best, sketchy in their interpretation of events. This has made it difficult to identify the mechanisms associated with lightning injuries or fatalities. As more research has been performed and experts have been involved in investigating the scenes, a better understanding has been obtained and methods to reduce exposure to dangerous events have been developed. A greater understanding has also been gained in the interaction of lightning currents and the bodies of living beings. This appendix highlights a number of lightning investigations that have occurred over the last 60 years. They have been conducted by researchers from different fields, primarily being the engineering, medical and health sciences.

Appendix B - Risk methods: Risk methodologies and the application of IEC 62305-2 can produce a variety of results. This is primarily because of the level or depth of the assessment being performed. In this appendix the risk analysis methods, as well as results from a number of simulations, are presented. These analyses were based on three residential structure types typically found in South Africa.

Chapter 2

Lightning mortality and morbidity

This chapter presents lightning death and injury statistics from around the world. The data provides insight into the location, gender and age distribution of lightning fatalities and injuries. The collection of this sort of data has, for many years, been reliant on press and general media sources; however, more countries are now creating dedicated records of lightning fatalities.

2.1 Lightning statistics

Reporting of lightning injury and fatality statistics from around the world has increased over the last few decades (Cuenca *et al.* (1992); Elsom (2001); Gomes & Kadir (2011); Holle (2012*a*); Dlamini (2009); Pinto *et al.* (2010); Mulder *et al.* (2012)). The accuracy and completeness of the data is, however, questionable. There are certain countries where deaths are recorded, but not necessarily always classified, and these files have, in some cases, been used to report lightning fatality. However, even lightning deaths are sometimes misreported, as an eyewitness may not be available and no autopsy is performed, and therefore the wrong classification of death may be applied. Injuries, however, are seldom ever logged and, therefore, information regarding such events must be obtained from some media source. As a result of this, there may be many rural events which are never known about. Under-reporting is a major concern and, in most cases, it is assumed that, for every death that occurs, there are approximately ten injuries. Holle has performed many analyses of lightning death data, obtaining the information from archives and various media sources. He is often referenced with statistics indicating that there are approximately 24 000 lightning deaths per annum and, therefore, 240 000 injuries (Blumenthal *et al.* (2012); Pinto *et al.* (2010); Berger

(2007); Holle (2012*b*)). This is based on the global lightning death statistic of 6 deaths per million people. However, the current world population is just over 7 billion people, which would effectively double this to 48 000 lightning deaths per annum. In 1976, Weigel (1976) published an article which indicated that, at that time, lightning was the number one killer in the United States. He goes on to highlight a number of lightning safety tips and then does some statistical analyses. Finally, he listed 90 cases of lightning related injuries and fatalities from July 1974 to June 1975.

Berger (2007) considers that most data relating to lightning deaths and injuries is under reported. His reference is to data obtained from the United States, where there were 33 % more lightning deaths in Texas than reported storm data had recorded. In a similar way in Colorado, there were 28 % more lightning fatalities, and 42 % more lightning injuries, than had been reported.

A collection of lightning statistics from around the world will now be presented. These focus primarily on lightning fatalities; however, reporting on injuries is also included. Cooray *et al.* (2007*a*) suggests that the number of lightning incidents in the tropics is probably higher than other areas, primarily because of the higher ground flash density, and because time spent outdoors, or in unprotected structures, is high. However, this data is not available as there is no reporting. In addition, lightning is a relatively inconsequential concern when compared to basic necessities, influence of disease, and provision of food.

2.1.1 USA

With regard to lightning statistics, Holle (2003, 2012*a*,*b*) has, over the last few decades, analysed and compiled most of the recorded lightning data for the United States, as well as world trends. Though not all information gathered from the press is comprehensive, it certainly provides a starting point. Other researchers have also compiled lists with slightly varying values, Cuenca *et al.* (1992), 2574 fatalities; Cooray *et al.* (2007*a*), 2566 fatalities and 6720 injuries, for the period of 1959 - 1985, but the variation is minimal. Rakov & Uman (2003) comment that the reporting of lightning statistics is questionable, as the reporting mechanism is not comprehensive and it has been found that, in collecting data in the United States, both under and over reporting occurs. However, lightning is still considered to be the second highest cause of storm related deaths in the United States, behind flooding.

Every alternate year, the International Conference on Lightning Protection (ICLP) is held, where research in all aspects of lightning is presented. In 2012 this was held in Vienna, where Holle presented a collation of a number of his previous papers (Holle (2012*b*)). The main period examined was from 2001 to 2010, and, in all cases, sufficient evidence was presented to attribute the fatality to a lightning event. It is estimated that the number of injuries is approximately a factor of 10 greater than that of the fatalities, but this is still an unconfirmed statistic. The findings of Holle indicated that the states within the USA with the greatest number of lightning fatalities are in the south-eastern region, with the exception being Colorado. The Rocky Mountains influence the weather conditions and, therefore, the lightning occurrences. *Table 2.1* shows a list of the states with the highest recorded lightning fatalities.

Table 2.1: States in the USA recording the highest number of lightning fatalities (Holle (2012*b*)).

State	**No. of deaths**
Florida	62
Colorado	26
Texas	24
Georgia	19
North Carolina	18
Alabama	17

An analysis, performed by medical personnel, of the number of deaths due to lightning in North Carolina from 1978-1988, showed that only 23.9 % of the fatalities occurred in an urban environment (Cuenca *et al.* (1992)). Of the 46 deaths recorded, 83 % occurred outdoors, and 78.3 % were male. In 26 % of all cases, a tree was involved. From the data collected, recreation activities near water accounted for almost 20 % of all deaths. The results of autopsies performed on the victims are summarised in *Table 2.2*.

2.1.2 Canada

Mills *et al.* (2008) collected data from a variety of sources, they found the annual lightning fatalities in Canada to be between 9 and 10 persons, with the number of injuries varying between 92 and 164. Similar to other countries' statistics from around the

Table 2.2: Medical examiner's report of fatalities due to lightning in North Carolina (1978-1988) (Cuenca *et al.* (1992)).

Finding	**Number**
Cardiac arrest (Witnessed)	5 (10.9%)
Cerebral infarction/edema	7 (15.2%)
Myocardial infarction	3 (6.5%)
Pulmonary edema	2 (4.3%)

world, the majority of victims are male (84 %), under the age of 46, and are involved in some outdoor activity. Mills also determined that there is an underestimate of lightning mortality by 36 %, and morbidity by between 20 and 600 %. The data presented is from 1921 to 2003 and, during this time, 999 fatalities were recorded.

More detailed analysis was performed between 1994 and 2005. From these findings, the average annual death rate is 3.5 people, and injury rate is 16.4 people. These values, when adjusted to population figures, are 0.65 injuries per million people and 0.11 deaths per million. Within this time period, the majority of deaths were male aged between 16 and 46. They accounted for 72 % of all deaths and 77 % of all injuries (Mills *et al.* (2008)). Once more, the highest fatalities (70 %) and injuries (62 %) occurred when some outdoor activity was being performed. The primary activities, with the highest mortality rates, were camping and hiking (20.8 %). Boating (15.1 %), picnicking (9.4 %) and golf (7.5 %) also featured often in the research. Incidents with a high number of injuries usually related to a sport, and the two most common games are soccer and baseball. Mills also mentions that, where more detailed analysis of the incident in the report is given, the majority of fatalities and injuries, 68 % in each case, occurred to people in open spaces or taking shelter under a tree.

2.1.3 UK

The Tornado and Storm Research Organisation (TORRO), in the United Kingdom, has a database which records incidents of lightning. Elsom (2001) extracted information from the database for the period of 1993 - 1999, during which time a total of 341 people were affected by lightning. Most people suffered only minor injuries, a few people suffered full thick burns, or required resuscitation. A total of 22 people were killed by lightning over the period, therefore averaging 3 deaths from lightning per year (Cooray *et al.* (2007*a*)). Elsom described that the UK has seen a steady decrease in lightning fatalities over the last few decades. Between 1852 and 1899, 193 people were killed, this dropped to 115 for the next half century and, finally, 54 between 1950 and 1999. On average, males accounted for 4 out of every 5 deaths. All fatalities recorded between 1993 and 1999 occurred outdoors, and the relative locations are presented in *Table 2.3*. Elsom determined that a fatality occurs once in every 4 events. This is irrespective of population figures and based purely on the events that occurred. Approximately 52 % of all incidents experienced in the UK between 1993 and1999 occurred indoors, 25 % of which involved a telephone. As in most societies, the general move away from agricultural activities, the increase in city size, higher urban population densities, and greater awareness of the dangers associated with lightning, has led to the steady decrease in fatalities.

Table 2.3: Lightning fatality locations recorded in the UK between 1993 and 1999, (Elsom (2001))

Location	**fatalities**
Open sports fields, farm field or park	7
Sheltering beneath trees	4
Hill or cliff top	3
Fishing	3
Tent	1
Holding umbrella on a golf course	1
Other	3

2.1.4 Asia

Most Asian countries do not have any official organisations or groups who collect lightning related data. Also, because of the large rural populations, as in Africa, many cases are never reported, or lack confirmed witness accounts, so the cause of death is not correctly recorded.

In Malaysia, the lack of knowledge or understanding of the dangers of lightning means that protection measures are not put in place and, therefore, there has been an increased number of injuries and fatalities, shown in *Table 2.4* (Kadir *et al.* (2012)). The primary source of information for the statistics of lightning related events has been medical records and newspaper articles. It is felt that the lightning death data is more accurate as this is, generally, officially reported somewhere. Lightning injuries are, however, seldom accurately reported and, therefore, official figures are unknown. The majority of the fatalities are associated with outdoor activities. There is also a large component of farming that occurs during the monsoon season, thus placing many more people in dangerous scenarios.

Table 2.4: Number of lightning fatalities in Malaysia between 2008 and May of 2012 (Kadir *et al.* (2012)).

Year	**No. of lightning deaths**
2008	19
2009	25
2010	12
2011	30
2012 (May)	45

In a paper published by Cooray *et al.* (2007*a*), Sri Lanka records approximately 50 deaths from lightning a year. Gomes *et al.* (2006) investigated lightning incidents in Bangladesh and Sri Lanka. In 2005, 73 incidents of lightning were investigated in Bangladesh, which resulted in 133 deaths and 137 injuries. In 2003, 35 incidents of lightning were reported in Sri Lanka, which resulted in 49 deaths and 18 injuries. 55 % of all were from side flashes occurring to people seeking shelter under a tree. 30 % of casualties occurred inside a structure; 75 % of these were people living in small shelters with a metal roof, and brick, wood or clay walls. Of the accidents occurring outdoors, the activities included:

- Agricultural
- Riding bicycles
- Swimming in open water
- Hiking

2.1.5 China

Zhang *et al.* (2012) provides details of lightning incidents from the National Lightning

Hazards Database in China . During a 13 year period, between 1997 and 2010, there were 5352 deaths and 4931 injuries as a result of lightning. 50.8 % of all fatalities occur in rural environments. The average lightning ground flash density across China is 4.22 flashes/km^2/year. However, the eastern humid region experiences ground flash densities of 31.44 flashes/km^2/year. The lightning fatalities and injuries are presented in *Table 2.5.* Of the lightning fatalities in the rural environments, the location of the fatalities is shown in *Table 2.6.* It can be seen that 79 % of all fatalities occurred in open spaces.

Table 2.5: Lightning injury and fatality distribution for the whole of China (Zhang *et al.* (2012)).

Location	**Percentage (%)**
Rural fatalities	50.8
Rural injuries	33.1
Urban fatalities	3.6
Urban injuries	4.2
Unknown	8.2

Table 2.6: Lightning fatality distribution in rural areas of China (Zhang *et al.* (2012)).

Rural fatality location	**Percentage (%)**
Farm	37
Buildings, factories & building sites	16
Open fields	14
Water fields	9
Mountains	7.5
Trees	7
Telephones and radios	5
Bikes and motorcycles	4.5

2.1.6 Europe

The following are statistics provided by various researchers, but often did not form part of their main topic.

- In Switzerland, 12 lightning deaths occurred between 1988 and 1992 (Cooray *et al.* (2007*a*)).
- In Germany, 19 lightning deaths occurred between 1991 and 1993 (Cooray *et al.* (2007*a*)).
- In Austria between 1990 and 2005, there were 65 lightning strikes resulting in injuries, and 9 lightning strikes resulting in deaths (Kompacher *et al.* (2006)).
- In Poland between 2001 and 2006, there were a total of 60 deaths. This is broken up into 45 (75 %) men and 15 (25 %) women (Loboda (2008)). In the same period, a different data set indicates that there were 61 injuries over the same period. In some of the data available, more specific details are provided regarding the adverse event. Of these, 36 % of cases occurred under trees, and 40 % occurred in open areas, this includes mountains, country, beaches and sport fields. Out of all lightning events, only 32 % resulted in a fatality.

2.1.7 Brazil

Pinto *et al.* (2010) published lightning statistics for Brazil in 2010, looking at events that occurred over the last decade. The data gathered came from a number of sources, but did include the Federal Civil Defence Agency and the Ministry of Health. 1321 lightning fatalities were recorded over a ten year period, which indicated an annual average rate of 0.7 deaths per million people. As has been seen in other data, there is a higher percentage of men who were killed than women, in the ratio of 5 to 1. The age group with the highest number of fatalities was 10 to 39, as has been seen with other data as well. 85 % of the fatalities occurred in open areas, 19 % of the fatalities occurred while performing agricultural activities, 12 % occurred when people took shelter under a tree, and 10 % while playing soccer. The ratio of injuries to fatalities was not published in the paper.

2.1.8 Africa

As in Asia, because of the population distribution being primarily in rural areas and, in addition, the ancestral beliefs, many fatalities are not reported. As a result, except for those cases stated for specific countries, very little data is available. Cooray *et al.* (2007*a*) does state that in Zimbabwe between 1965 and 1972, 430 deaths were recorded. These values are considered, on a world standard, to be quite high.

2.1.9 South Africa

Initial lightning related fatality information was produced by Eriksson & Smith (1986). The data was collected primarily from newspaper articles and announcements. The work was performed over a period of 15 years, and from this it was determined that the death rate in an urban environment is approximately 1.5 deaths per million. However, in rural environments this increased to 8.6 deaths per million. This is as a result of the large rural population in South Africa and, therefore, the exposure to lightning as a result of everyday activities. A recent study by Blumenthal (2005), investigated 38 lightning fatalities, over a three year period, for the highveld region of South Africa. The information was collected from six medicolegal mortuaries, which serve a population of approximately 7 million people.

- 38 reported cases
- 52 % witnessed lightning strikes
- Average age was 36 years old
- 79 % were male
- 92 % were of the black race group
- 97 % of the cases occurred outdoors
- 37 % of the events occurring outdoors were located in open fields

The research showed that in 38 % of the cases, singed hair was recorded, a thermal injury was noted in 89 % of the cases, with 47 % experiencing third-degree burns.

2.1.10 Malawi

Mulder *et al.* (2012) recently published a paper reporting lightning injuries and deaths for the Nkhata Bay district, Northern Province, Malawi. The data dates from the first event recorded, in 1979, up to 2012. During this time, 225 events occurred, which resulted in 454 injuries. Of these, 117 victims died. 15 % of the victims who survived had a permanent injury. The statistics collected for the period of 2007 to 2010 show a considerably higher number of victims than for the average of the whole period. This may be as a result of under-reporting from earlier times. From the recent statistics, the annual expected death rate from lightning is in the order of 84 deaths per million per year. There has been no official reporting structures for lightning related events. The data presented in the paper came about from three surveys conducted through the community.

2.1.11 Swaziland

Dlamini (2009) compiled data of lightning fatalities for the period 2000 to 2007. The survey obtained information from two sources, initially from media reports and, from 2002 onwards, the Royal Swaziland Police Service records were used. Dlamini indicates that there is still potential under-reporting of fatalities. A total of 123 fatalities occurred in the 8 year period, which, based on a population of approximately one million people, means an annual fatality rate of 15.5 deaths per million people. The fatality ratio between men and women is 2.1 to 1. Two large lightning incidents occurred during the period. The first occurred in Mbeka, in 2003, where 9 people were killed and 7 were injured. The second recorded no fatalities, but 70 boys were injured during a traditional ceremony.

Table 2.7: Lightning fatalities associated with various activities in Swaziland (Dlamini (2009)).

Activity	**Percentage fatalities**
In house	17 %
Walking home	16 %
Under tree	14 %
Church service	8 %
Bus stop	2 %
Herding cattle	2 %
Unknown	34 %

Unlike many of the other findings, the majority of events occurred while being indoors. The definition here, however, is different to first world countries, as the structures are typically made of straw, and have mud floors. Therefore, this statistic cannot be associated with traditional urban indoor environments. The most common values are shown in *Table 2.7.* The only indoor activity seen on the list relates to church services, however these are not necessarily permanent structures, and in some instances these services are conducted outdoors.

2.2 Classification of human activities with a high lightning hazard

Bernstein (1973) wrote, in a paper in the Journal of Forensic Sciences in 1973, the following:

> "*There seems to be a definite pattern for the activities or location where a person is apt to be injured by lightning. Locations or activities that seem to occur quite regularly are near a tree, on a golf course, on a tractor, using a telephone, near a clothes line, near a wire fence, and in a boat. Larger groups of people are injured in military camps while in the field or on athletic fields.*"

For a statement made over 40 years ago, it certainly seems that no progress has been made. There are still many lightning related injuries and fatalities that occur in open spaces, and though there is significantly better understanding, warning systems and social media tools, tragic events still occur.

The distribution of locations where lightning fatalities occur in the United States are (Rakov & Uman (2003)):

1. Open fields, ball fields, parks, etc - 28 %
2. Under trees - 18 %
3. Boating, fishing, water-related, etc - 13 %
4. Golf courses - 6 %
5. Farming, construction, near heavy machinery, etc - 4 %
6. On telephone, radios, electronics, etc - 1 %
7. Various others / unknown - 30 %

This information was gathered from *Storm Data* from the US National Climatic Data Centre

In almost all reports, the general world trend, when looking at lightning fatalities, is decreasing. One of the primary reasons for this is that significant urbanisation has occurred over the last 50 years. This, in combination with greater understanding of the phenomenon and the risks associated with it, and an increase in safety awareness, contributes to the declining number of fatalities. Dr M.A. Cooper has spent much time over the last couple of decades promoting lightning safety within the United States (Cooper (2008); Cooper & Kadir (2010); Zimmermann *et al.* (2002)). In addition, she has helped developing countries with such objectives as trying to decrease lightning deaths.

Trees are often used as a means to avoid getting wet during a thunder storm. This is why a large percentage of recorded fatalities occur near trees. Holle (2012*a*) compiled statistics from around the world with respect to deaths and injuries of living beings near trees. Sources for the data included, but were not necessarily limited to, internet posts, newspaper articles, published papers and general publications. The summary of this data is shown in *Table 2.8.* There is a heavy bias towards the US in the data as this information is more readily available, whereas in third world countries such news may not be reported and, therefore, has no chance of appearing in any media sources. One reported incident occurred in January 2004, 60 people were injured in Swaziland as they took refuge from a storm, under a tree.

Table 2.8: Data collected from various sources relating to lightning deaths and injuries near trees (Holle (2012*a*)).

Location	**Events**	**Deaths**	**Injuries**
United States	328	156	662
Non- U.S.	116	206	439
Total	444	362	1101

Holle extracted from the data, where more information was provided, the relative position of the victim to the tree, during the lightning strike. These are quite subjective results, as the details were not personally investigated by Holle, but relied on reporters to provide sufficient detail. This data is presented in *Table 2.9.* Many injuries recorded when the relative position to the tree was included, showed that injuries occurred between 1.5 and 10 metres from the tree. The recorded deaths in the same situation were as a result of the person being directly next to the tree, or between 2 and 10 metres from the tree.

Table 2.9: Relative position to trees, where living beings have had some form of interaction with lightning (Holle (2012*a*)).

Activity	**Events**		
	U.S.	**Non - U.S.**	**Total**
Under tree(s)	123	77	200
Near tree(s)	95	15	110
Forest/woods/grove	10	2	12
Between trees	8	1	9
Fallen branch/tree	7	1	8
In tree	3	3	6
Exploded tree	2	2	4
Orchard/tree farm	1	3	4

Holle (2003) identified a number of common outdoor activities, and investigated the lightning related events that occurred around them. The activities included soccer, baseball/softball, golf and camping (including tents). The list Holle presents is in no way comprehensive, but it provides an interesting overview of what has occurred. The results are shown in *Table 2.10*.

Table 2.10: Sports and outdoor activities, from around the world, where lightning deaths and injuries have occurred (Holle (2003)).

Activity	**Events**	**Deaths**	**Injuries**
Soccer	21	36	248
Baseball/Softball	18	9	95
Golf	38	23	56
Camping (tents)	29	11	125

The high counts pertaining to soccer are generally as a result of third world countries, where shelter from rain is often sought under trees. Golf courses are dangerous for both players and people working on the courses. Adequate protected shelters should be provided for protection of all groups.

2.3 Summary

The general trend of lightning injuries and fatalities has been on the decline since the beginning of the last century. In most cases, this is as a result of movement away from intensive agricultural activities in rural environments. Third world countries, because of the higher rural populations, and the type of daily activities, tend to exhibit higher lightning fatality statistics. These communities often have higher incidences of multiple injuries or fatalities, as protection from storms is often sought under trees.

The increased urbanisation has not been without its injuries and fatalities. These, though, are now typically associated with recreational activities, where general activities being performed before the onset of the storm include; agriculture, golf, fishing, swimming, walking in a park, cycling. Therefore, warning measures and protection plans should be considered to reduce the number of incidents associated with lightning. The dangers of lightning to living beings in outdoor environments is known, however the presented data still indicates that insufficient knowledge regarding the dangers of lightning is held by the general public. Thus, adverse events are still relatively common with respect to recreational activities.

In the next chapter, the physical parameters of lightning, and how it interacts with grounded objects, are presented. In addition, the currently accepted methods of determining what objects require protection and what relative safety this affords the surrounding area is considered.

Chapter 3

Physical world parameters during a lightning strike

In this chapter, general lightning parameters are presented. Three areas are presented which include the latest South African lightning ground flash density data. The parameters of the electrical properties of a lightning stroke are discussed; these affect the way lightning interacts with different ground-based objects. In addition, general information regarding the interaction of a lightning stroke with the ground is presented. Finally, different methods used in determining the preferential point of strike are discussed. These methods also provide a means of determining the areas afforded protection from lightning by a tall structure or object.

3.1 Lightning ground flash density data

South Africa has, for many years, used data collected by the Council for Scientific and Industrial Research (CSIR) regarding lightning ground flashes. The map shown in *Figure 3.1* was created using data collected over an eleven year period (Gijben (2012)). The system comprised of 400 counters, deployed throughout South Africa and Namibia (Anderson *et al.* (1984)). This map has been used for a number of decades and the data from the system was incorporated into the South African lightning standards, SANS 10313: The protection of structures against lightning.

In 2005 the South African Weather Service installed a lightning detection network. Data from the first five years of installation has been published and the results are shown in *Figure 3.2* (Gijben (2012)).The general lightning ground flash density trend for the two maps is very similar. There is, however, a marked difference in the number of flashes per square kilometre per year. The average value for the Gauteng region, in South Africa, was originally taken as being between 7 and 8 flashes/km^2/year. From the new map, this value has increased to between 10 and 15 flashes/km^2/year. This shows an increase of between 40 and 100 %.

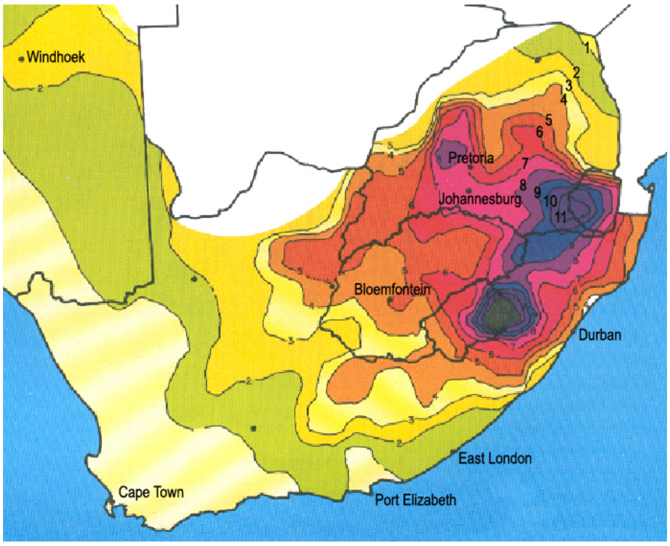

Figure 3.1: CSIR lightning ground flash density map for South Africa, 1994

This marked increase could be related to two things. Firstly, the new lightning detection network is supposed to have a 90 % detection efficiency (Gijben (2012)). Therefore, it is possible that the old network simply did not detect all events. Secondly, there is a thought that there is a correlation between the number and intensity of lightning strikes, and global surface temperatures. The main implication of this marked increase is that the risks previously associated with lightning are considerably higher.

Dwyer & Rassoul (2009) consider that, with an increase in surface temperatures, the energy available, as well as the amount of moisture in the upper atmosphere as a result of evaporation, would increase, thus resulting in more lightning, as well as a greater intensity. Price (1993, 2008) has written and presented a number of works on lightning and climate change. In 1993 Price indicated that it would be useful to be able to correlate global temperature rises with some non-linear relationship. A comparison of the relationship between ionospheric potential and surface temperature indicates that a 1 % surface temperature increase would see about a 20 % increase in ionospheric potential. In the same paper, Price suggests that an increase in global warming by 4 °C

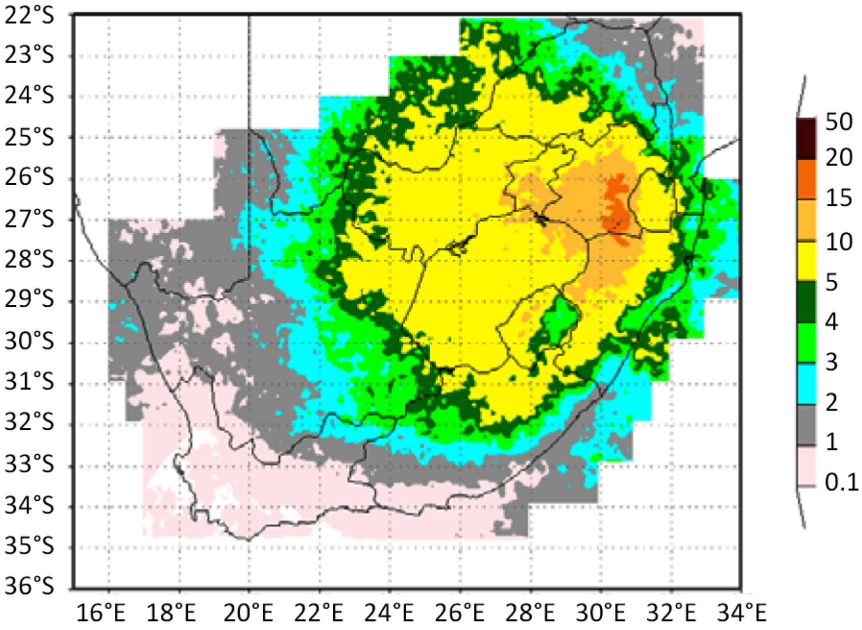

Figure 3.2: South African Weather Service lightning ground flash density map of South Africa (Gijben (2012)).

could result in a 30 % increase in global lightning frequency. 15 years later, at the International Conference on Lightning Protection, Price presented a keynote address. He presented a paper on the relationship of thunderstorms, lightning and climate change (Price (2008)). He suggests that tracking the lightning activity may present insight into certain parameters associated with climate change. Further, it is noted that lightning intensity seems more prevalent in drier environments, therefore indicating the difference between African and South American lightning activity. What has been noted is that there is a positive relationship between temperature and lightning, with lightning increasing anywhere from 10 to 100 % for every one degree of surface warming (Price (2008)). Price does indicate that there seems to be some contradictions in the process, as an increased upper atmosphere temperature should result in a smaller atmospheric lapse rate, showing, therefore, a decrease in lightning activity. However, short term measurements, as well as various models, all indicate that an expected 1 K temperature rise would result in approximately 10 % more lightning. Two main points come from this. Price is in agreement with Dwyer that there may be fewer storms, but that the intensity of the lightning would increase. Secondly, moisture content is crucial in understanding the whole system, with an increase in upper atmospheric moisture providing a positive feedback into the system, thus aiding global warming.

3.2 Lightning parameters

3.2.1 Peak current (I_p)

Through Ohmic resistances, the peak current will create a potential difference. As a result of this, dielectric breakdown can occur. This may result in some damage, but this usually only occurs in systems where the earthing and bonding is not sufficiently low, or is not present (Cooray (2003)). This principle can also apply to objects such as trees (Rakov & Uman (2003)). The application of Ohm's law allows for the determination of the voltage which, with respect to a distant object, may be substantially higher.

3.2.2 Peak current derivative (di/dt)

di/dt will create a voltage drop across an inductor, and can also be responsible for induced voltages. Many severe problems result from this aspect of a lightning strike, particularly with respect to protection systems. Considerations should be given to development of a system capable of handling 100 - 200 kA/μs (Cooray (2003)). This is calculated using $V = Ldi/dt$, which provides the potential difference over an inductor. Within the context of an earthing system, with possible potential rises as a result of the inductance of the protection measures, the incorrect bonding of electronic devices can easily result in the damage of these items (Rakov & Uman (2003)).

3.2.3 Total charge (Q)

This is determined by integrating the measured peak return stroke current. The result of large continuing currents, lasting a couple of hundred milliseconds, can result in damage. However, in the case of metal conductors, penetration of heat into some metal conductors is still not possible, as current duration is too short (Rakov & Uman (2003)). There is typically a very small voltage drop across objects, in this case, being in the order of 5-10 V. However, if the pulse length is sufficiently long, the charge transfer can be quite substantial.

3.2.4 The action integral ($\int i^2 dt$)

This relates to the energy absorbed in 1 Ω when lightning current flows through it (Cooray (2003)). The action integral of lightning is significantly higher than other fast transients. The action integral is used primarily to understand the thermal effects in ohmic resistances. It is often the case that mechanical destruction to a device or object will occur before the thermal effects are sufficient to cause damage. However, it relates to the melting of resistive materials, which are typically good conductors, and to explosions of poor conducting materials (Rakov & Uman (2003)). About 5 % of negative first strokes in ground flashes have action integrals exceeding 5.5×10^5 A^2s, and, in the same bracket, for positive strokes, the action integral may exceed 10^7 A^2s. In many cases of poor conductors, this heat vaporises the internal material, and the gas pressure can result in an explosive fracture.

3.3 Point of strike

When the downward stepped leader reaches a height of a couple of hundred metres above the ground, the electric field at the tip of grounded structures increases to such a level that electrical discharges can be initiated. This can, in time, result in a stable, upward propagating leader. The connecting leader travels towards the down-coming stepped leaders. Connection will be made between one of these upward leaders and the downward leader. The connecting leader, which bridges the gap, will define the point/object that is identified as having been struck by lightning (Cooray (2003)). The "striking distance" can be defined as the distance between the tip of the downward leader and a point on an earth object where the critical electrical field has been reached (Uman (2008)). The typical electric field for breakdown at standard temperature and pressure is $3 \times 10^6\, Vm^{-1}$. The breakdown field is lower at higher altitudes.

The equation to describe the striking distance is based on the electrogeometric model (Uman (2008); Cooray (2003); D'Alessandro (2003)):

$$d = AI_p^b \tag{3.1}$$

where

d = Striking distance [m]

I_p = Return stroke peak current [kA]

A, b = Constants

Various researchers have proposed different values for the constants used in equation 3.1. The equation provides a starting point for the development of a lightning protection system. However, Uman states that no two situations are the same, therefore defining a unique equation to define all possibilities cannot be done. The IEC has adopted values of 10 and 0.65 for A and b respectively. Whereas Cooray *et al.* (2007*b*) defined values of 1.9 and 0.9. This effectively halves the striking distance used currently by the IEC, shown in *Table 3.1.* One note, however, is that this was work is based on attachment to flat ground and therefore, once an object is placed in the study area, it may be found that the striking distance is larger.

Table 3.1: Comparison between values obtained from the IEC and Cooray's striking distance models.

Striking distance model at 20 kA	**Distance (m)**
IEC (10, 0.65)	71
Cooray (1.9, 0.9)	29

The incidence of lightning to a ground-based object can be calculated using a formula proposed by Eriksson (Metwally & Heidler (2007)), defined as:

$$N_i = 2.4 \times 10^{-5} H^{2.04} N_f \tag{3.2}$$

where

H = Height of object [m]

N_f = Ground flash density [$km^2/year$]

Eriksson's derivation of this formula came from analysis of recorded data from lightning strikes to a 60 m tower. Therefore a comparison would not be drawn between the *Equations 3.1* and *3.2.*

In IEC 62305-2 (IEC (2007*c*)), an equation for the incidence of lightning to a structure per year is defined. This equation is defined as:

$$N = A_d N_g \times 10^{-6} \tag{3.3}$$

where

A_d = Collection area of the object [km^2]

N_g = Lightning ground flash density [flashes/km^2/year]

The collection area A_d for a structure, is defined as:

$$A_d = LW + 6H(L + W) + 9\pi \cdot H^2 \tag{3.4}$$

where

L = Length [m]
W = Width [m]
H = Height [m]

The collection area is related to three times the height of the structure. Metwally & Heidler (2007) propose a method using an extended geometrical model. The work aimed at identifying which conductor used in an air termination system would be most often struck, and therefore increased the accuracy and benefit of a risk analysis. Metwally considers that the average incidence is not altogether inaccurate. However, the introduction of the location factor in the IEC 62305-2 standard results in an over estimation of the probability of the effect of the surrounding objects on the analysis. The simulations performed indicate that the influence may only be in the order of 10 %, rather than the 25 % presently used in the standards.

3.3.1 Protection angle

The angle of protection was adopted by the IEC, and has been incorporated as a method of determining the protection provided by air termination components for a structure. The determination of the angle of protection and its application are summarised as (IEC (2007*d*)):

- Height of the termination conductor above the object to be protected.
- The protective angle is dependent on the level of protection required.
- The angle of protection is different for different heights of the termination conductor above the area to be protected.
- There are geometrical limitations of the angle of protection. Therefore, if the height 'h' is too high, the rolling sphere method must be used.

The angle of protection is obtained from a graph in IEC 62305-3 (IEC (2007*d*)). The lightning protection level must first be chosen before the angle can be determined. The height 'H' is the height of the air-termination system above the plane to be protected. From these two values, the angle of protection can be determined. If this plane is less than 2 m from the top of the mast, the angle of protection does not change. In *Figure 3.3*, the mast tips are located at 2.3 m and 3.7 m above the roof plane, and 10.3 m and 11.7 m above the ground plane. Therefore, with respect to the protection to the ground reference plane, each mast has an angle of protection of approximately 45°, and, in the case of the roof top plane, the angle is 70°. The shaded region is the area that should be protected by the masts.

In the case that a tall structure is being assessed, the rolling sphere method should be used instead of the angle of protection. This is because there are many tall structures which have not had attachment to the top of the building, but rather to some distance down the side of the building.

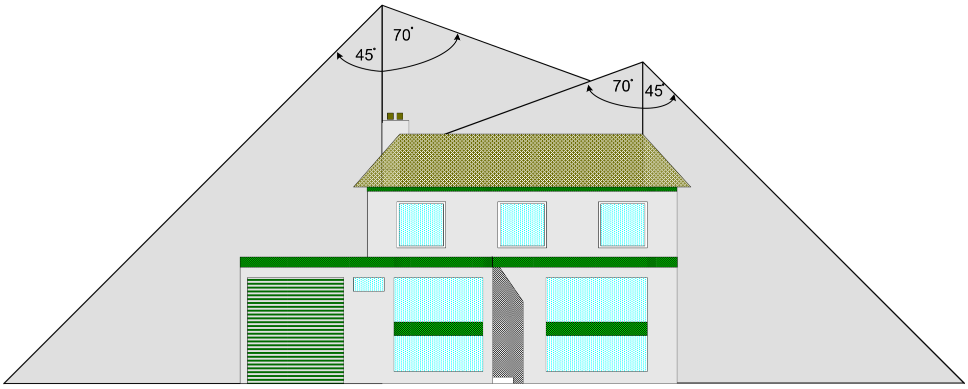

Figure 3.3: A residential structure, with two lightning masts. The angle of protection for each mast is shown.

3.3.2 Rolling sphere method

The rolling sphere was developed from the equations used to define the striking distance. The lightning protection level defines the diameter of the rolling sphere. The sphere is then rolled over a building and any point where the sphere comes into contact with the building indicates a point at which lightning attachment can occur. This also shows areas that would be deemed to be relatively safe from a direct lightning strike. The size of the sphere is determined from the peak return stroke current value. The values for the radii of the spheres are 20, 30, 45 and 60 metres for lightning protection level class of I through IV. If a structure's height is greater than the radius of the rolling sphere, then lightning attachment is not necessarily limited to the top of the structure.

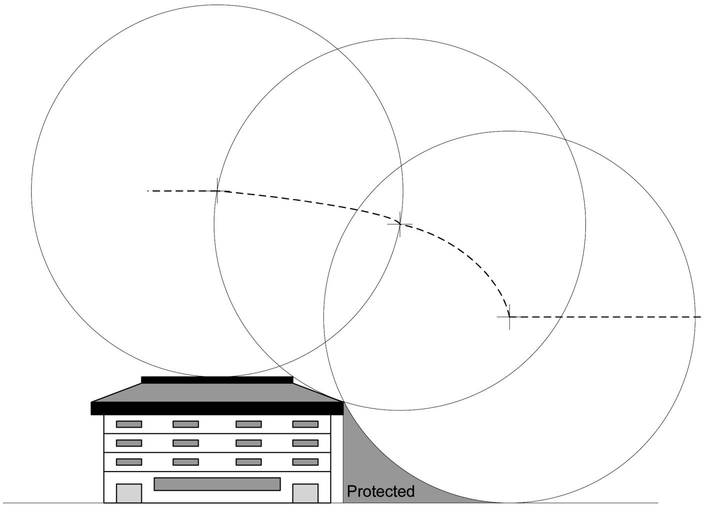

Figure 3.4: Applying the rolling sphere model to a structure. The area where the sphere is in contact with the structure could be a point of attachment, therefore requiring some form of protection. The shaded area represents an area that is safe from direct attachment. The dotted line represents the expected striking distance for the structure.

3.3.3 Collection area defined

The collection area is used in lightning risk assessments, IEC 62305-2, to determine two things. The first is the effective ground-based area of a structure or object that would result in a direct strike to the structure or object. The collection area is calculated using 3 times the height of the structure under investigation, shown in *Equation 3.4*. The second relates to the effective area surrounding a building where, if a strike occurs, there could be magnetic coupling between the lightning current channel and the electrical installation of a building. This is defined as a radius of 250 m away from the structure. This would be affected by things such as the density of surrounding structures. Electromagnetic coupling can, however, occur at significantly greater distances than this. *Figure 3.5* shows a structure consisting of two distinct sections, A and B. Using each section's height, the collection area (striped region) can be determined and drawn. This area is calculated using *Equation 3.4*.

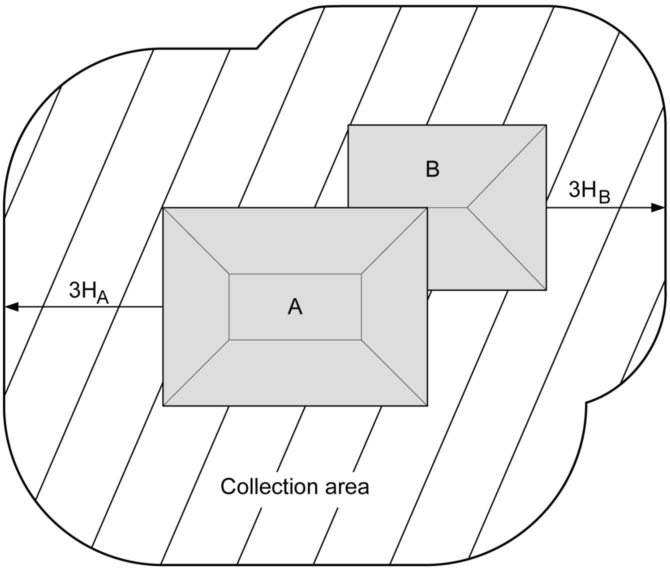

Figure 3.5: The collection area is used primarily when using the IEC 62305-2 to determine the risk of lightning damage to a structure. The striped region defines the collection area.

3.3.4 A lightning strike to trees

In many scenarios there are trees surrounding an object being assessed. The NFPA 780:2004 discusses the concept of trees and lightning protection. The recommendation is that any tree within 3 m of, or that has branches over, the structure, should have its own protection (Uman (2008)). There has been some research regarding strikes to trees, however, no conclusive proof is provided which determines if one tree is more prone to a strike than another. Mäkelä *et al.* (2009) investigated a number of lightning interactions with trees and poses, and attempts to answer, certain questions.

One question that is posed by Mäkelä is; are trees growing in the open, or on the edge of a forest, more likely to be struck? The answer to this has more to do with the observer than anything else. It is merely that these trees are seen to be struck more often than those in the middle of a forest (Mäkelä *et al.* (2009)). He also debunks the concept that the tallest tree is struck, with the science of the conductivity of the tree defining which tree may get struck.

- The highest trees are the most likely to get struck? Their analysis, though not conclusive, does indicate that there is no correlation between strike probability and the height of a tree. Components such as water content, as well as general conductivity, would also have an influence on this.

- Trees growing in the open, or on the edges of forests, are more likely to be struck? This is skewed by the observer. As it is not possible to have researchers following a storm and noting where and what is struck, the analysis is left to eye witnesses, who would naturally see these trees before those in the middle of a forest. Therefore, there is no conclusive proof.
- Trees growing in poorly conducting ground are more likely to be struck? This is highly dependent on soil moisture content and water type. Measurements would need to be conducted to verify this, but the thought, in fact, is that the better the conductivity of the soil, the more likely a strike to a tree will result. However the result is still uncertain.
- Ground moisture affects tree damage? Ground moisture has more to do with the most recent amount of rain. An increase in ground moisture would indicate that rain has recently fallen. If rain has fallen within the three hours prior to a strike to a tree, the tree has a lesser risk of being damaged.
- Poor quality trees are more likely to be destroyed? Older trees tend to have areas of previous damage, soft pulp, and the ingress of water. In addition, voids or ruptures can aid in the lightning current flowing through the tree. This, in turn, may lead to a greater risk of damage occurring.
- Close by grounding can protect a tree? This is inconclusive in the study. It was found that the presence of a nearby good electric ground does not affect the damage.
- Positive currents cause more damage? Statistically inconclusive, however, 28 % of the cases investigated were related to positive flashes. This value exceeds the average positive lightning strokes for Finland, thereby indicating that positive lightning strikes are more likely to cause observable damage.
- High peak currents correspond with more extensive damage? This theory is supported. More explosive cases were associated with higher peak current values. In the case of negative strokes, -32 kA was the average peak, and 37 kA was the average positive peak.

These questions were raised from the investigation of 37 incidents of trees being struck by lightning. One of the conclusions made during the research, is that the electrogeometric method does not necessarily predict the strike probability to a given tree, with particular reference to the tallest tree being the one to be struck (Mäkelä *et al.* (2009)).

Heidler *et al.* (2004) suggests a distance of 3 metres should be kept from the branches and the trunk of a tree to minimise the potential for a side flash. He also suggests keeping the feet next to each other to reduce the chance of a step potential. The work performed pointed out that blunt trauma could also be a real concern. A fir tree struck by what has been determined as a positive lightning stroke, resulted in tree fragments, weighing between 20 and 70 kg, being found up to 50 m away. Smaller pieces, weighing between 1 and 10 kg, were found more than 80 m away.

3.4 Interaction of lightning current and the earth

When the lightning current reaches the earth, the current disperses radially outwards from the point of strike. If an earth termination is the path into ground, the current is dispersed through low impedance conductors with relatively safe dispersion of the current into the earth. If there is no low resistance path into the ground, the current through the earth results in surface voltage potentials on the ground. If the current peak magnitude or the soil resistivity is high, excessively high ground potentials can result. The voltage is seen to roll off from the point of strike at a rate of $1/r$. In certain cases the lightning strike may result in surface arcs, which can contain a considerable portion of the lightning current from the original channel.

3.4.1 Earth resistivity

The impedance of soil is primarily dependant on the water content and its relative resistivity (Uman (2008); Rakov & Uman (2003)). Hummel presented an equation that will define the earth resistivity based on the relative amount of water and its resistivity. The general values of soil resistivity are defined in *Table 3.2*. These are approximate values and will vary from site to site.

Measures can be taken to decrease the ground resistance using a variety of chemicals. These are typically used when attempting to reduce the impedance of an earth electrode.

Table 3.2: Soil resistivities for a variety of different soil types (Uman (2008); Rakov & Uman (2003)).

Types of soil	Resistivity (Ωm)
Clay	25 - 70
Sandy clay	40 - 300
Peat, marsh soil & cultivated soil	50 - 250
Sand	1000 - 3000

3.4.2 Surface arcs

Surface arcing has been seen in both rocket triggered lightning experiments, and in laboratory tests (Fisher *et al.* (1994); Uman (2008)). The distribution of the arc from the point of strike is random and, in a number of events recorded, the arc formation was never the same. Fisher *et al.* (1994) performed work looking at electric fields and earth currents using rocket triggered lightning. The findings of the work, though limited to only 7 events, showed that, if the peak return stroke current is above 15 kA, surface arcs were present every time. The range of the arcs and the percentage of current flowing in them, is still uncertain. However, in one event, 5 % of the peak return current was measured in a surface arc coming in contact with the measurement system.

Simulations in a laboratory, which resulted in surface arcs, were performed on loamy soil which had been sprayed with water to simulate rain. The electrical properties were a soil resistivity of 270 Ωm and a peak input current of 20 kA (Uman (2008)). Rocket triggered experiments at Fort McClellan indicated that surface arcs as long as 20 m, and possibly longer, are possible (Rakov & Uman (2003)).

3.5 Summary

In this chapter, general lightning parameters have been presented. The annual expected lightning ground flash density maps for South Africa were presented. The new LDN lightning ground flash density data shows a significant increase in the number of ground flashes in comparison to the original CSIR map. This would indicate that the risks in general are higher than previously determined.

The electrical parameters of lightning were presented, indicating how lightning interacts with different objects, whether it is related to voltage gradients causing side flashes, or heating of conductors. The angle of protection, rolling sphere and collection area methods were also presented. These are merely tools to help in the design of an LPS for a structure, or determining the expected annual number of events, thus a means of determining the risk of lightning to an object. Finally, soil resistivity and the development of surface arcs was discussed.

These are all factors to determine the risks associated with lightning and earth based objects. However, the subtle variations between scenarios result in making the equations required to solve for the risk very broad. The application of the equations presented in *Section 3.3* on how lightning can interact with specific objects in a defined space, may provide better understanding for determining the risk of lightning.

In the next chapter, the relationship between these lightning components and living beings is described. This will look at the electrical impedance model of living beings, and the mechanisms of injury and death.

Chapter 4

Lightning and living beings

In this chapter, three sections are considered. Firstly, the electrical properties as well as an equivalent circuit model of the human body are presented. This includes descriptions of cells and their surrounding fluids and therefore how electrical current may interact with tissue. Secondly, the mechanisms of lightning injuries are described, as well as what damage electrical current passing through the body may cause. Finally, a discussion regarding a number of lightning incidents that have been published is presented. In many cases, large groups have been involved, which result in both fatalities and injuries.

4.1 Introduction

Significant work has been performed in trying to understand how electricity interacts with the human body. This arose through the necessity to understand how electrical injuries occur, and what levels of protection are required. In addition, work was performed to enhance the bioengineering field, with reference to life saving equipment and components. There are, however, many parameters that are still not understood and thus, provide opportunities for further research.

A large percentage of the currently applied principles and understanding was developed during the latter half of the 20^{th} century by the likes of Dalziel, Lee, Ishikawa and Kitagawa (Dalziel & Lee (1968); Kitagawa *et al.* (1973); Ishikawa *et al.* (1985)). Investigations were performed on animals, ranging from mice, rats and rabbits, to pigs, sheep and dogs, and, in certain instances, human subjects were exposed to a variety of impulses. A book on "Electrical injuries" by Fish, provides one of the most complete collections of information regarding electrical injuries, from both mains power and lightning (Fish & Geddes (2009)). The book also covers subjects such as pacemakers and tasers.

The original work by Dalziel & Lee (1968), proposes an equation for the current limit that the human body can be exposed to, this is defined by equation 4.1. Dalziel's work determined that the two critical parameters are; the body weight and the duration of exposure. This equation is defined for a body weight of 50 kg, but has a sliding scale for the 'K' factor. The experiments performed used power frequencies (50/60 Hz), and the equation is only valid for a duration of between 30 ms to 5 s. At the same time, in Japan, Kitagawa, Ishikawa and Ohashi were conducting experiments on a variety of animals and dummies (Kitagawa *et al.* (1973); Ishikawa *et al.* (1985); Kitagawa *et al.* (1985)). Their research indicated that there is a lethal energy limit after which death occurred. This limit is determined to be 62.6 J/kg (Kitagawa *et al.* (1973)). Bernstein (1973) notes that the lethal energy may actually be between 25 and 50 joules. Szczerbiński (2003) considers that the lethal energy limit is actually far broader than Kitagawa concluded, indicating that energy between 10 and 50 joules is sufficient to result in ventricular fibrillation (VF).

Dalziel's equation for the current limit to avoid VF is (Dalziel & Lee (1968)):

$$I_{cr} \leq Kt^{-0.5} \tag{4.1}$$

where

$K = 0.065$ to $0.165\,\mathrm{As}^{-0.5}$, according to weight
$t =$ Shock duration [s]

Ossypka's formula was similar, but looked at the charge transfer rather than a peak current. These two models were based on 50/60 Hz, and therefore will differ from that of a lightning impulse.

4.2 Electrical model of the human body

Most calculations performed using the human body, result in a lumped resistance of between 800 and 1000 Ω being used. Andrews indicates that the human body can have an internal resistance of between 300 and 5000 Ω (Cooray (2003)). The circuit diagram of the human body's lumped resistance per limb, including contact resistance, is shown in *Figure 4.1.* The diagram includes the parallel *RC* components which are used to model the contact resistance. This model has been reproduced in a number of different publications, and though there may be subtle variations in the component values, this is the common base from which work is performed.

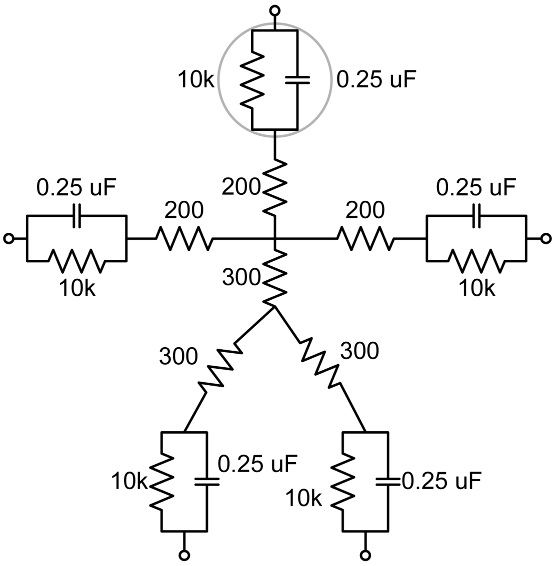

Figure 4.1: Conventional impedance model defined for humans. All resistance values are in ohms (Fish & Geddes (2009)).

There are currently a number of computer models of the human body that have been generated to be used for simulations. The *Human-body-model* and *Voxel* model are examples used in electrical simulations. These models can be integrated into a variety of simulation software packages (Suchanek *et al.* (2012)). The Voxel model was developed using contiguous slices of computer tomographic (CT) scans of the body. Andrews (Cooray (2003)) considers that the body impedance is known to a greater or lesser degree, as they have been reasonably well documented. This includes parameters such as the influence of pathway, contact voltage, area of contact and frequency. Andrews considers that the impedance model of the body can be closely estimated, therefore these models should be respected when performing lightning calculations. The resistances of different tissues in the body have been measured, and though the values differ, there is consensus in the scale of resistivity: nerve → blood vessels → muscle → skin → tendon → fat → bone (Cwinn & Cantrill (1985)). Though Andrews still identifies that there has been a lack of work being performed on current paths and magnitudes through the body, because of the ethics associated with humans being shocked in a laboratory. This confirms the thought that, though the models provide very good approximations, there is still scope for further work.

The skin is made up of both a resistive and capacitive component. The skin comprises of the epidermis and dermis. The epidermis is considered to be a bad conductor, as many of the cells are dry and dead (Fish & Geddes (2009)). The epidermis could be considered as equivalent to a dielectric, therefore, if a conductor is present on the skin, this, in conjunction with the conductive tissue below the dermis, forms a capacitor. Therefore, the skin can be modelled as a capacitor in parallel with a resistor. The resistance of the skin is affected by the moisture, cleanliness, thickness and vascularity (Cwinn & Cantrill (1985)).

In some experiments, it was attempted to determine the capacitance of the human body. Experimental results showed that the values are between 95 and 398 pF, with an average value of 205 pF. It was also proposed that the body should be modeled as a 100 pF capacitor, in series with a 1500 Ω resistor. The skin impedance varies by the presence of moisture, condition of the skin, temperature and local blood flow as a number of examples, therefore resulting in a wide range of resistances, from 1 000 up to 100 000 Ω. SANS IEC 60479-1 (IEC (2006)) presents data from measurements performed to determine the total body impedance for a range of frequencies at 10 V. At 10 kHz, the total body impedance is approximately 900 Ω. This value is measured from hand to hand, in dry conditions. The experiment was repeated on a single person at 25 V, and only up to 2 kHz. This showed that the body impedance is approximately 600 Ω at 2 kHz. This work indicated, that as the frequency was increased above 2 kHz, there was no significant change to the bodies impedance.

4.2.1 Properties of tissues

Miklavčič *et al.* (2006) investigates the nature of biological tissues, in trying to define the current paths through the human body. The relative permittivity of biological tissue has a tendency to drop as the frequency increases. Therefore, what is seen is that the conductivity of the tissue remains relatively constant, increasing only in the MHz range. At the nominal lightning frequency of 10 kHz, the conductivity is seen to be below 0.2 S/m, and the permittivity is around 5×10^4 F/m. Miklavčič also highlights the complications with dielectric measurements of tissue, particularly those that are anisotropic. This becomes irrelevant at high frequencies, in the order of megahertz. Except for these anisotropic tissues, most tissues show no frequency dependence between 100 Hz and 100 kHz. This would be in agreement with the IEC 60479-1 standard, where the body impedance, when tested at values above 1 000 V, for increasing frequencies, does not have a significant change (IEC (2006)).

The different biological tissues of the body all have their unique electrical properties. In all cases, however, it is possible to model them as a collection of parallel resistors, in series, with a capacitance, shown in *Figure 4.2.* There is a resistance which can be equated to the low frequency resistance of extra-cellular fluid, which is R_e. The parallel branches are the intracellular resistance and capacitances, R_t and C_j respectively (Ruan *et al.* (2009)).

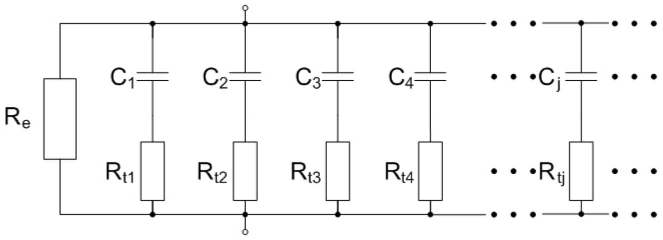

Figure 4.2: Circuit diagram of the intracellular resistance and capacitance (Ruan *et al.* (2009)).

4.2.2 Dangers to living being physiology - Killing parameters

Two bodily functions are vital for survival, the first is the operation of the lungs, or the supply of oxygen to the body. The second is the circulation of blood around the body, or the operation of the heart. If either of these fails, the effect on the human body is catastrophic. In any electrical interaction with the human body, the components that need to be considered are; the magnitude of the current, the duration, and path of flow. The avoidance of a current flowing through the head or chest cavity greatly aids in reducing the risk of the loss of life during an adverse event. Many physicians have misreported lightning fatalities by recording the death as a result of a cardiac arrest (Cwinn & Cantrill (1985)).

Burns can result in the destruction of vital organs, blood loss, electrolyte imbalance, infection and, in addition, high body temperature can be fatal (Fish & Geddes (2009)). An arc in contact with a person can result in serious burns, or in burning of clothes, which can result in secondary complications in time, such as infections.

Asphyxia is death by suffocation. Breathing in the body is controlled by the brain, and in the event that current flows through the respiratory centres in the brain, (Brain stem, pons and medulla), respiratory arrest (central apnea) may occur (Cooray *et al.*

(2007*a*); Bernstein (1973)). Typically this would be as a result of a shock that occurs between the head and a limb, or between the arms. There is no means of automatically correcting this, and it will ultimately result in the body being starved of oxygen. Lack of oxygen reaching the brain quickly leads to the death of brain tissue (Cooray *et al.* (2007*a*)).

Ventricular fibrillation, or the uneven beating of the heart, eventually results in the ceasing of the heart. This is usually fatal because the heart muscles move independently. Cardiopulmonary arrest, the absence of systole, is the major cause of death following a lightning strike. Mortality from this is approximately 20 %. This results from depolarisation of the myocardium, and could lead to myocardial dysfunction, including arrhythmias (abnormal heart rhythms). Cardiac arrest is either a complete standstill (asystole), or unsynchronised contraction pattern of the myocardium, called ventricular fibrillation (VF). It is possible, in the event of a cardiac arrest from a current flowing through the body, that the heart will recover naturally as it has an inherent "pacemaker" (Cooray *et al.* (2007*a*)).

Muscular contraction (a power related problem) is the inability of the muscles of the body to overcome the effect of the power system in contact with the body, therefore sustaining the dangerous situation.

Burns result from the heating of the tissues (Electrocution). Burns may be full or partial thickness burns, ranging in length between 1 and 4 cm. Generally they occur in regions of heavy sweat, and may, in some cases, only appear hours after the strike (Cwinn & Cantrill (1985)).

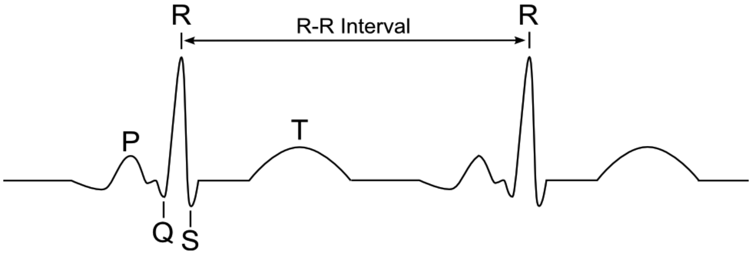

Figure 4.3: An illustration of an electrocardiogram (ECG) for a heart, indicating the 3 visible operations (P,QRS,T), (Burke (2008)).

The electrocardiogram (ECG), shown in *Figure 4.3*, is used to monitor a heart's operation. The heart has four operations, however, only three are seen on an ECG, as two events overlap. The first is called the P wave, which occurs when the atrial depolarises. The QRS complexes occur when the ventricular depolarises, and finally, the T wave occurs as a result of ventricular relaxation, or repolarisation of the muscles.

The T waveform, as mentioned, is the relaxation period of the cycle, and is believed to be the most vulnerable time. In an analysis performed by Stramba-Badiale *et al.* (1997), the ECG for a group of healthy males and females was investigated. The T wave section differed between the two groups. In men, the peak is lower and the duration is shorter, when compared to females. In the case of males, the T wave constitutes approximately 8.3 % of the heart cycle and for females it is approximately 13.4 %. This has close agreement to Bernstien, who indicated the T wave occurs for approximately 150 ms out of a total period of 750 ms for the heart cycle (Bernstein (1973)).

Fish & Geddes (2009) describe the current and duration required to evoke a cardiac contraction, which is in the region of 10 mA for a duration of 0.05 ms. A single external stimulus of adequate intensity, delivered during the late recovery (repolarisation), will initiate ventricular fibrillation. Tests have been performed where capacitors were discharged across the chest of dogs. The results showed that fibrillation can occur at any stage of the heart cycle if the voltage is sufficiently high (Bernstein (1973)). From IEC 60479-3, for the threshold of ventricular fibrillation to occur, as the duration of the current flow increases, the minimum fibrillating current decreases. So, for current flowing for a duration of 0.2 of a heart period, the current required for ventricular fibrillation is approximately 3 A. In the case of the current flowing for a duration of 3 heart beat periods, the current required is approximately 285 mA. This duration is 15 times longer, and the current is 10.5 times less. Then the question is; if the heart rate is elevated, is the resultant current level and time duration required to initiate VF still within the time frames previously mentioned? Would this place people performing some form of strenuous outdoor activity at a higher risk of being affected by a lightning strike?

It is considered that a current of 0.75 mA to 4 A applied to the heart could cause VF (Cwinn & Cantrill (1985)). Larger currents will cause asystole with subsequent spontaneous restoration of normal sinus rhythm. Current of 100 mA or less can result in respiratory arrest as a result of paralysis of the respiratory centre. The duration of apnea, rather than that of asystole, appears to be the critical factor in morbidity and mortality. Transient hypertension and tachycardia have frequently been reported after a lightning strike, and are caused by endogenous catecholamines.

Mechanisms proposed to account for cardiac damage:

- Coronary artery spasm and additional arterial thrombosis.
- Catecholamine-mediated injuries.
- Direct thermal injuries.
- Ischemia secondary to arrhythmia-induced hypo-tension.
- Coronary artery ischemia as part of a generalised vascular injury.
- Electrical currents can damage the walls of the coronary arteries, there may also be a direct thrombogenic effect.

In IEC 60479-2 (IEC (2007*a*)) the relationship of different current paths through the human body, and the effect this has on the heart, is described. This is referred to as heart-current factor and is defined by:

$$I_h = \frac{I_{ref}}{F} \tag{4.2}$$

where

I_{ref} = The body current from the left hand to the feet [A]
I_h = The body current for a chosen current path [A]
F = The heart-current factor

As an example, if a current through the body, from the left hand to either of the feet is 90 mA for 1 second, it is assumed VF is probable. The equivalent current required from the back to the right hand, ($F = 0.3$), that may result in VF, is 300 mA. In the scenario of a step potential, if current flows from the right foot to the left ($F = 0.04$) a current of 2.25 A is required. These values are, however, for frequencies between 15 and 100 Hz. No work to date has shown an equivalent current relationship for frequencies between 5 and 50 kHz.

The nervous system is complex and damage may result in long term pain syndromes, well after physical injuries have cleared. Both the central and peripheral nervous systems can be affected. 70 % of all lightning survivors have some form of neurological injury (Cooray *et al.* (2007*a*)). In the nervous system, the following acute traumatic injuries may result: various types of intracranial haemorrhages, swelling of the tissues (oedema) and neuronal injuries. A lightning strike can also result in intense vasospasm and constriction of blood vessels, restricting blood flow (thus reducing oxygen to a part of the body), which may result in brain damage, delayed onset of neurological disturbances such as epileptic seizures, tremor, progressive hemiparasis, malfunction of nerves, and neurological defects in the central nervous system. Of particular importance is “keraunoparalysis”, which is the flaccid paralysis of an extremity in the path of the current, such as facial nerve palsy. This is thought to be caused by the damage of small blood vessels accompanying the nerves that control the muscles of the extremity involved, along with ischaema of these muscles (Cooray *et al.* (2007*a*)). These often resolve spontaneously.

Many forms of cutaneous lesions may be produced, depending on the current flow through or over the skin. Various skin markings may occur, which have various names, but are generally referred to as Lichtenberg figures. These markings usually resolve themselves within 24 hours (Cwinn & Cantrill (1985)).

Injuries sustained to the eyes and ears are also common, with tympanic membrane rupture being the most common otic injury. Cataracts are often seen to develop after a lightning event, and can occur any time from a couple of weeks or months, up to years later. In addition, corneal ulcers, retina detachment, and optic nerve injury may occur. Blunt trauma may also result, commonly attributed to muscular contractions, or the shock wave from lightning. These parameters are still questionable, but may occur. Partial paralysis may result in more blunt trauma, especially to the head, as a victim collapses.

In SANS 60479-3 (IEC (1998)), the impedance of animals is described. These experiments were, however, all performed at 50/60 Hz and 230 V. It provides a starting point for any analysis but, again, this does not necessarily allow for extrapolation to higher frequencies.

4.2.3 Physiological and neurological sequela of lightning injuries

Electroporation is used in molecular biology as a method to introduce a foreign gene or protein material into a host cell. Electroporation may be responsible for cell death in the case of an electrical injury. Fish & Geddes (2009) indicate that, though electroporation has been implicated in cell death in electrical injuries, this has not been demonstrated in lightning injuries. Ritenour *et al.* (2008) feels that the process of electroporation may explain why there is a delayed presentation of neurological sequela following a lightning injury. Fish also indicates that delayed diagnosis of injuries relating to the spinal cord could be as a result of electroporation, or dielectric breakdown of cell membranes due to high voltage gradients. Though there is still no correlation between lightning and electroporation, because of its transient nature, it is uncertain if the process can occur in such time frames.

The majority of sequela following a lightning strike are neurological, and these occur in 70 % of survivors (Cooray *et al.* (2007*a*)). Gatewood & Zane (2004) describe some of the sequela experienced by moderately injured victims being; sleep disorders, irritability, difficulty with psychomotor functions, parasthesias, generalised weakness, sympathetic or nervous system dysfunction, and post traumatic stress syndrome. In addition, atrophic spinal paralysis has been reported, though this is rare.

Nervous system injury causes the greatest number of long term problems for survivors. The central, peripheral and sympathetic nervous systems can all be damaged (Gatewood & Zane (2004)). Current through the brain can result in coagulation of the brain substance, formation of epidural and subdural haematomas, respiratory centre paralysis, and intraventricular haemorrhage. Lightning victims almost universally demonstrate anterograde amnesia and confusion, regardless of whether they were rendered unconscious or not. These symptoms can last for hours or days. Pain and paresthesias are prominent features of peripheral injury. Symptoms can be delayed from weeks to years. In severely injured lightning victims, nearly two thirds of patients demonstrate some degree of lower extremity paralysis (keraunoparalysis). Many victims of lightning injury exhibit unrelenting headaches for the first several months following lightning injury. Many suffer from nausea and severe, unexpected, frequent vomiting episodes. Dizziness and tinnitus are also common complaints.

Cataracts most commonly develop within the first few days, but can occur as late as 2 years after the event, and are frequently bilateral.

Psychological dysfunction

Lightning victims can present many different neurocognitive deficits, which need to be carefully assessed. These can be described as (Gatewood & Zane (2004)):

- Functional issues
- Behavioural issues
- Depression

- Marked diminution of
    - short-term memory ability
    - attention span
    - mental agility
- No task coordination
- No ability to follow orders for complex tasks that would have been easy before the event
- Increased aggression
- Extreme fatigue
- Sleep disturbance or hypersomnolence
- Flashback and nightmares
- Avoidance of precipitant circumstances, consistent with post-traumatic stress disorder

4.3 Mechanisms of injury

Mechanism of lightning strike, and *mechanism of lightning death* are two considerations when investigating a lightning event (Blumenthal (2012*a*)). The mechanism of lightning death was considered in the previous section, this section will consider how lightning interacts with living beings and thus results in injuries and death. Cooper has performed extensive work in detailing lightning pathology and developing lightning education, in the United States, and around the world. Cooper presented the information shown in *Table 4.1.* The data of the distribution of lightning injuries was collected from incidents around the world (Cooper (2008)).

4.3.1 Direct strike

The termination point is on the body, usually on the head or upper torso, thus exposing the body to the full lightning current (Cooray *et al.* (2007*a*)). In the case of a direct lightning strike, very little current may actually flow through the body. As the potential increases with a rise in the current, there comes a point where the potential is sufficient

Table 4.1: Mechanisms of lightning injury (Cooper (2008)).

Mechanism	**Frequency**
Direct	3 - 5 %
Touch potential	1 - 2 %
Side flash	25 - 30 %
Ground potential rise	30 - 50 %
Upward streamer	20 - 25 %

to cause breakdown of the air along the skin. This path is considerably lower in impedance than the impedance of the body and, therefore, the parallel paths would result in the majority of the current flowing on the outside of the body. By considering these paths and the possible current level, as well as the duration of the impulse, it can be seen that the energy flowing through the body could be considerably lower than the 62.6 J/kg required for death. The surface discharge, however, may result in burn injuries.

4.3.2 Touch potential

In the event that an object is struck and a living being is in contact with the object, multiple current paths can be created. If the current through the body is sufficient, then this could result in death. The touch potential, in many cases, provides a path for the current, that often goes through the chest cavity, thus increasing the chances of current paths through the heart. The nature of the mechanism also means that flashover is unlikely to occur, increasing the peak current flowing through the body. Szczerbiński (2003) looks at a scenario for touch potentials, indicating that a mean critical energy of 30 J is obtained, with a minimal resistance between the contact point and a hand being approximately 210 mΩ. This would hold for the majority of cases and therefore should always result in a fatality.

4.3.3 Flashover or side flash

A side flash occurs when an object is struck and the developed potential at some height 'h', is sufficient to result in an arc over to a nearby object, as shown in *Figure 4.4*. Flashover requires sufficient voltage to develop so that breakdown of the air can occur,

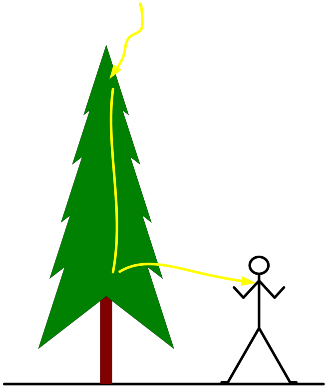

Figure 4.4: Side flash occurring to a person standing near a tree that has been struck by lightning.

therefore, attaching to a remote object. The electric field intensity is dependant on many parameters, but is considered to be between 300 and 500 kV/m (Uman (2008); Berger (2007); Rakov & Uman (2003)). Altitude and humidity have a substantial influence on the electric field intensity value. More than 50 % of all injuries from lightning are as a result of side flashes from trees (Cooray *et al.* (2007*a*)). This is considerably more than previously stated by Cooper, but does emphasise the risk of this mechanism.

An equation to define the potential developed as a result of a lightning strike to a conductor, is defined in *Equation 4.3*. The potential developed at a height 'h' above the ground is defined by (Rakov & Uman (2003)):

$$V(t) = R_{gr}I(t) + Lh\frac{dI(t)}{dt} \tag{4.3}$$

where

R_{gr} = Ground resistance of system [Ω]
$I(t)$ = Lightning current [kA]
L = Inductance of the down conductor [H]
h = Height above the ground [m]

Through his research, Shindo recommends that the minimum distance between a living being and an object, if outside during a storm, should be at least 3 m (Shindo *et al.* (2002)). He describes that certain recommendations and standards suggest that 2 m is sufficient. Some theoretical calculations, as well as tests in an outdoor high voltage laboratory, indicate that this should be increased to 3 m. The methodology looks at the expected breakdown in air and down the tree, and calculates the separating distances of the person and the tree. The possibility of flashover occurring in a scenario is higher if the potential developed on the tree is greater than that required to breakdown the distance between the tree and the person. Additional factors would need to be considered as mentioned earlier in *Section 3.3.4*.

Tests were performed in an outdoor high voltage laboratory using planted trees. The human was assumed to be a copper rod located at a distance '*d*' from the tree. This rod was driven into the local earth. Shindo's results demonstrated that the tree type has an effect on how, and whether, flashover will occur. The tests indicated that, in some cases, the flashover occurs along the branches and leaves to the object, and in other instances, there is a flashover from the trunk of the tree. Experiments to a larger, 13.25 m cedar tree, indicated slightly different phenomena, and therefore, the distance of 2 m may actually be acceptable. The surface flashover stress of the trees used in the initial experiments are equal to 350 - 400 kV/m. The work indicated that the lightning strike to the tree will perform differently in the majority of cases, as the conditions, as well as the tree type, all play a factor in the path that the lightning will take. Though the results were varied, the main conclusion still indicated that 2 m is insufficient to prevent a side flash from a struck object.

4.3.4 Step potential

Once a lightning strike reaches the earth, it is assumed to dissipate radially outwards. This creates potential gradient rings around the point of strike. *Figure 4.5* indicates the process where ring 'a' will be at a higher potential than ring 'b', and these values are dependent on the soil resistivity. The further apart the victim's feet are, the higher the potential gradient, therefore the bigger the current that can pass through the body. The current will typically flow up one leg and down the other. It is felt that the step potential is less likely to result in a fatality as the current would not encounter the heart (Cooray *et al.* (2007*a*)). However, currents flowing in the earth may be sufficiently large to result in shocks to multiple people near the location of a lightning strike (Rakov & Uman (2003)). In the event of a sitting or lying person, depending on the points of contact, the severity of injuries sustained could be significantly higher. In the case of quadrupeds, the development of a step potential can be very dangerous as the current will invariably flow through the thorax, and therefore introduce currents to the heart (Cooray *et al.* (2007*a*)).

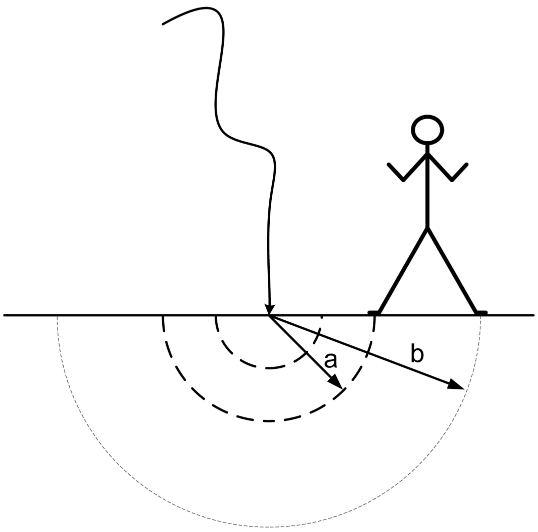

Figure 4.5: Figure indicating the development of a step potential across the body, relative to the point of strike.

Andrews, however, does indicate that there is a small amount of current that, in the event of a step potential, will reach the heart (Cooray *et al.* (2007*a*)). As the body is made up of many discrete components, the multiple paths of the current through the body would result in something going through the myocardium. A factor of 0.3 is stated. This obviously has to do with a number of parameters, but working with this factor, a step voltage of say 1 kV, could produce 1 A through the body and, therefore, 300 mA could go through the heart. With a short duration pulse, minimal effects would be expected at these low values; however, as the step potential increases, the chances of severe injury increase.

A second mechanism of step voltages is attributed to surface arcs, similar in nature to a side flash. Contact with a surface arc can result in burns and shocks, resulting in paralysis and even death (Rakov & Uman (2003)). Kitagawa (2000) presents a notion that currents through the upper layer of earth will exert shocks and a feeling of numbness but that is all. In the case of a surface arc, this can cause thermal injuries and paralysis, and could also result in death in the worst case scenario.

Pregnant women, and the risk to babies

Fetal injuries from electric shocks are not uncommon, and will often result in some injury to, or even death of, the fetus. Zack and Gatewood have both presented cases where a step potential occurred to pregnant women (Zack *et al.* (2007); Gatewood & Zane (2004)). Zack reported 8 lightning incidents to pregnant women, all women survived, but 4 fetuses died. Gatewood describes the prognosis of the fetus for pregnant women struck by lightning as being unpredictable. From case studies of 11 pregnant women, 5 of the pregnancies ended full term with live births, with no apparent abnormalities or injuries, 3 resulted in live births with neonatal deaths. The remaining 4 babies were still born or deaths in utero.

Physics of the step potential

Figure 4.5 shows that when a lightning stroke is injected into the earth, a person standing at some distance away will be subjected to a ground potential rise. The magnitude of this potential is dependant on their step length (a to b), the peak current, and the soil resistivity. The equation that defines the step potential comes from Kraus's far field approximation, and is defined by (Rakov & Uman (2003); Uman (2008)):

$$V_{ab} = -\int_{b}^{a} E_r dr = \frac{\rho I}{2\pi}\left(\frac{1}{a} - \frac{1}{b}\right) \tag{4.4}$$

where

ρ = Earth resistivity [$\Omega\, m$]
I = Peak current [kA]
a, b = Distance from point of strike [m]

Using *Equation 4.4*, the step voltages can be determined for a variety of currents, earth restivities and step lengths. *Figure 4.6* shows the step potential (kV) for an increasing distance from the point of strike. The graphs are for different soil resistivities, with a peak return stroke current of 20 kA in all cases. The step length in this case is 0.5 metres. *Figure 4.7* repeats the same cases, however the step length is increased to 1 metre.

In *Figure 4.8*, the step length is set to 0.5 metres and the earth resistivity is kept at 300 Ωm, and different peak return stroke currents are used. *Figure 4.9* repeats the process with the step length increased to 1 metre. The four graphs shown in *Figures 4.6 - 4.9*, all show that the developed step potential can be of a considerable level at a significant distance from the point of strike. Though death may not result, severe injury may occur.

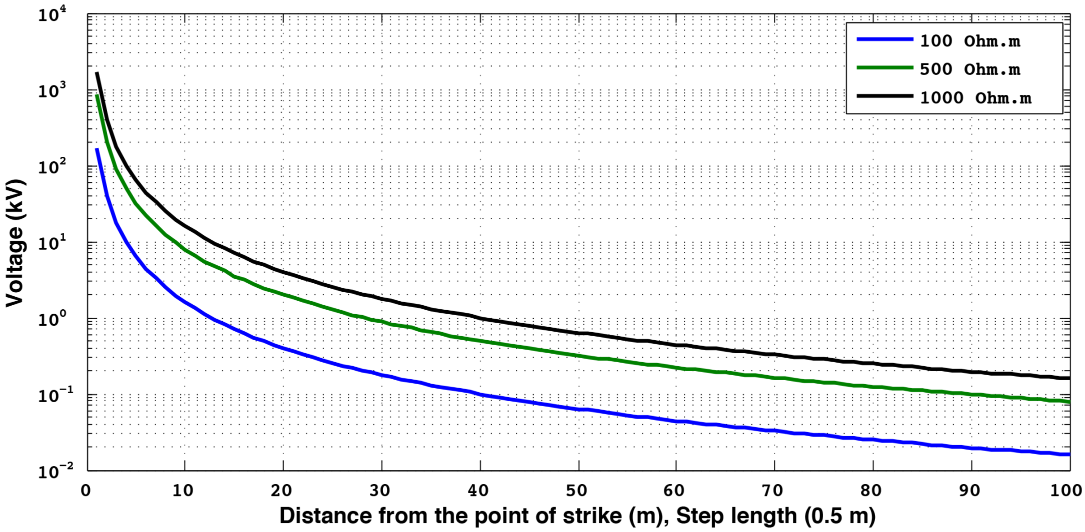

Figure 4.6: The step potential created by a peak return stroke current of 20 kA, at increasing distance from the point of strike, for three different soil resistivities. (Step length of 0.5 metres)

Contact resistance

The interpretation of the contact, or footing, resistance of a person to the ground, has been determined and is presented as (Cooray (2003)):

$$R_e = \rho/8b \tag{4.5}$$

where

R_e = Single foot resistance [Ω]
ρ = Earth resistivity [$\Omega\,\mathrm{m}$]
b = Radius of a flat plate representing one foot [m]

From *Equation 4.5*, the shape of the foot is represented by a circular plate of some radius, and the equation can be approximated to $R_e = 3\rho$. This is for a single foot in contact with the earth, and therefore needs to be halved if two feet are in contact with the earth.

4.3.5 Upward streamer

This mechanism of death is relatively new, and has only been considered in lightning incidents in the last few decades (Cooper (2000); Anderson *et al.* (2002)). The development of an upward streamer occurs from objects, as a downward leader approaches the

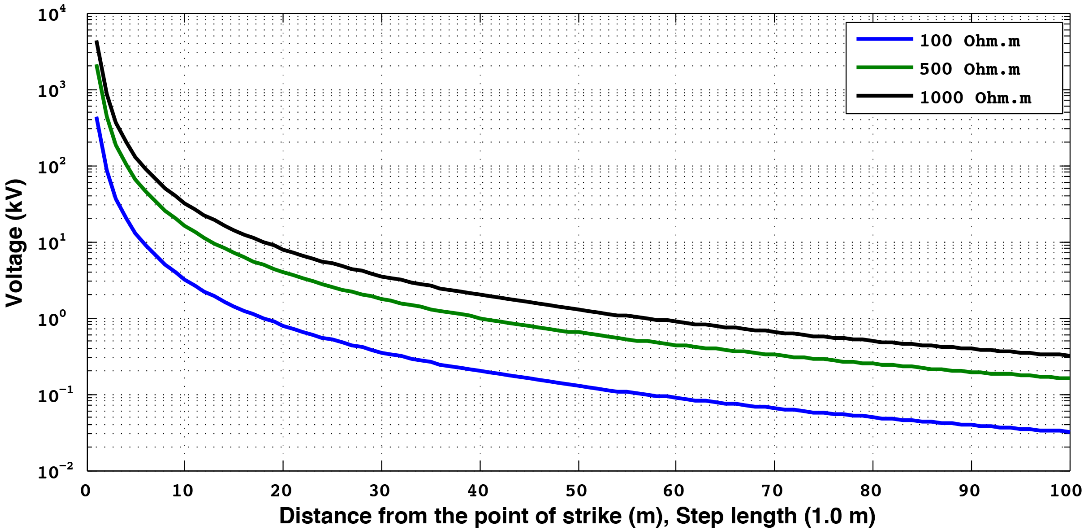

Figure 4.7: The step potential created by a peak return stroke current of 20 kA, at increasing distance from the point of strike, for three different soil resistivities. (Step length of 1 metre)

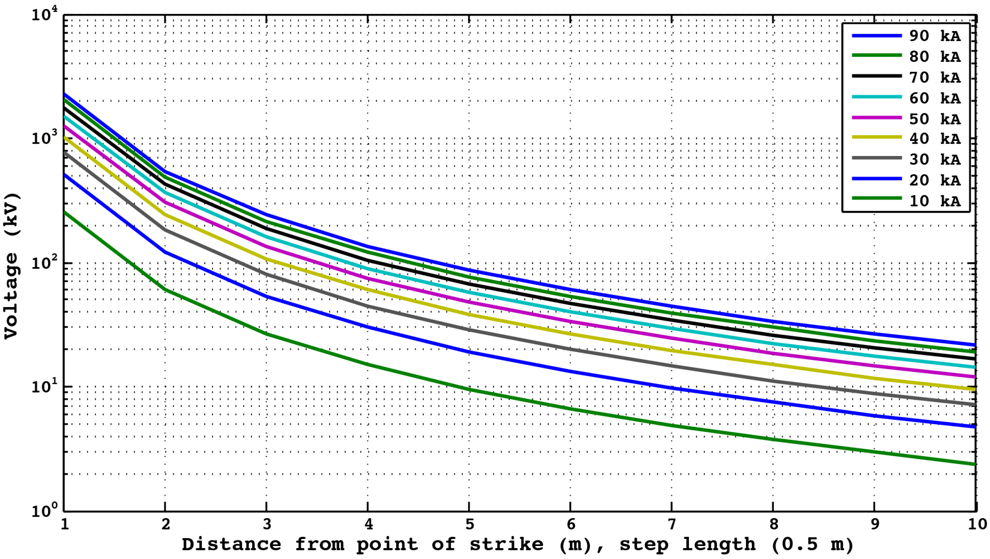

Figure 4.8: For a fixed earth resistivity of 300 Ωm, the step potential developed for a range of peak current. (Step length of 0.5 metres)

earth. Anderson *et al.* (2002) described this potentially deadly mechanism as a result of a number of injuries which occurred during a soccer match between two prominent South African football clubs . Seven players were injured, and four of those suffered serious injuries. Through studying the video footage, it become apparent that certain players that were affected did not have both feet on the ground at the time of the

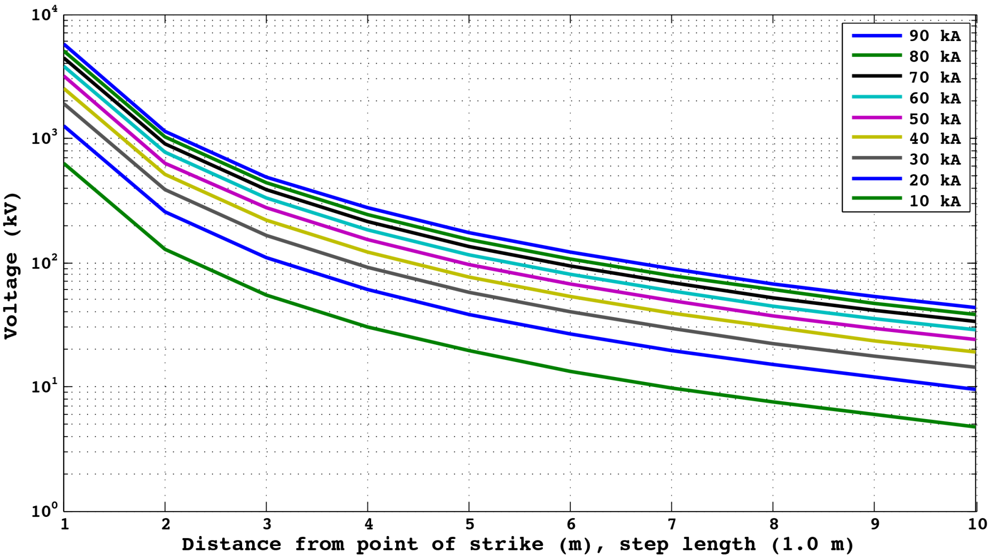

Figure 4.9: For a fixed earth resistivity of $300\,\Omega m$, the step potential developed for a range of peak current. (Step length of 1.0 metre)

strike, thus ruling out the possibility of the development of a step potential. The only plausible explanation was that, in the development of upward streamers, there is sufficient current flow through the victim to cause serious injuries. There is the possibility that sufficient voltage could be developed so that the rupture of the insulation of shoes may be possible, therefore resulting in a path to ground (Anderson *et al.* (2002)). The development of upward streamers can result in several hundred amps of current flow, for durations in the order of several tens of microseconds, which could be sufficient to cause injuries (Cooray *et al.* (2007*a*)).

4.3.6 Barotrauma and blunt trauma

The final mechanism is classified as lightning explosive barotrauma (Blumenthal (2012*a*,*b*)). This comes about from the forces associated with the lightning channel, resulting in ear drum perforation, or blunt force trauma injuries. The excessive temperature rise of the channel can cause a shock wave of orders of magnitude greater than the atmospheric pressure. In the same manner, a lightning strike to a tree can result in explosive forces that send shards of bark and wood flying away from the tree, which may result in injury and in partial destruction of an entire tree, which may result in a consequential death. Heidler *et al.* (2004) investigated some sites where trees were struck by lightning. Wooden fragments, weighing up to 70 kg, were found up to 50 metres from the tree trunk.

It is also considered that the contractions of the muscles can result in a bone fracture. This may be more probable in the power frequency range, although, during a lightning impulse, the forces produced may be able to fracture a bone. It is more probable, however, that the tendon would be torn off the bone, because of the time frames associated with a lightning impulse. It is more likely that a bone fracture would result from an impact with a projectile or fixed object.

4.4 Lightning injuries observed

In *Chapter 2*, lightning statistics from around the world were presented. It indicated that many fatalities occur outdoors, and in some cases provided some information regarding the event . In *Appendix A* a collection of lightning related deaths and injuries is summarised. These have been reported by a variety of different researchers, with specialities in engineering, medicine and health sciences. The case studies are in no way comprehensive, but they provide some important information.

Certain researchers such as Kitagawa and Ohashi have been investigating lightning incidents for a number of decades. Ohashi noted that in those incidents where flashover had occurred, there was a higher survival rate Ohashi *et al.* (1986). This lead Ohashi to investigate the effects of flashover and survival of a victim by experimenting on mice and rats. Many of the reports relate to a single lightning strike, where a group of people had gathered. These incidents provide a greater amount of information about the event. This is because there are a number of eye witnesses, the information regarding the event can be easily verified, and confirmed. If a single living being is involved, it is only the physical evidence found during the investigation that provides any clues to the event. In many of the cases reported, where a group of people were involved, only a few fatalities are reported. In a number of cases some injuries, and in some cases even death, occurred a number of days after the lightning event. In one case a child who was struck and was provided with extensive medical treatment and appeared to be stable, eventually died 24 hours later.

All the reports presented in *Appendix A* present cases where victims have been outdoors and have been subjected to either a direct or indirect lightning strike. There are very few similarities between cases and the outcomes in all cases were different. This highlights the uncertainty of what parameters actually result in a fatality from a lightning strike. Two points are uncertain to date. Firstly, the current path through the body is still relatively unknown. The conductivity of different tissues and organs in the body is understood, but the macro scale still has many questions. It is considered that, in most cases for human beings, a step potential would not result in a fatality. However, the current path associated with a step potential is still unclear, and Andrews does highlight that a small current will still go through the heart. The second is the physical path of the lightning strike. Is it more dangerous as it dissipates through the ground, thus resulting in a step potential, or if it arcs over the surface of the earth, thus resulting in a different interaction with the living being? These cases do, however, highlight the dangers of being outdoors during a storm, and if an understanding of the danger is known, why should any fatalities occur?

9 cases of animal fatalities are also presented in *Appendix A*, in which the increased dangers associated with quadrupeds can be seen. If a nearby lightning strike occurs, the number of fatalities is significantly higher, which would more than likely be as a result of the current paths through the thorax of an animal. This does, however, highlight the dangers to animals and the financial loss for farmers that is associated with a loss of animals. Therefore, it should be possible to determine the risks to animals and take action to guard against a fatal incident.

4.5 Lightning current parameters through the human body

Considerations are made regarding the parameters of the lethal energy limit, defined by Kitigawa, of 62.6 J/kg. Szczerbiński and Berger (Szczerbiński (2003); Berger (2007)) both consider that the value is overstated. Basic investigation of the probability of the development of flashover over a living being, and the number of fatalities, indicates that this critical energy level is not required to result in death. In the literature, a number of examples have shown that flashover should occur in the event of any direct lightning strike, thus limiting the current through the body and, therefore, reducing the risk of death considerably.

If the electric field required for breakdown in air is considered to be $500\,\mathrm{kV/m}$, and the height of a person is assumed to be $1.8\,\mathrm{m}$, then the expected breakdown voltage would be $900\,\mathrm{kV}$. If the impedance of the person is assumed to be $800\,\Omega$, then the current required for flashover to occur would be $1.125\,\mathrm{kA}$. This would collapse the voltage and the impedance in the air would be assumed to be approximately $2\ \Omega$. If the median lightning level is considered (20 kA), then the potential developed would be 40 kV, which would result in a current of 50 A through the body. For a duration of 10 ms, the energy would be 400 J, which, assuming a mass of 70 kg, would mean an energy of 5.7 J/kg. This is well below the lethal limit and, therefore, would indicate that the person should survive.

4.6 Discussion

Kitagawa *et al.* (1985) defines that there are three scenarios associated with a lightning strike to a living being. These will have an effect on whether the living being sustains an injury or the result is death.

- When the lightning current is very low, the path will typically be through the body.
- When the current level is sufficiently high, surface arc flashover develops on the body.
- When the current increases even more, a surface arc flashover occurs from the point of lightning contact to the ground. The majority of the current flows through the arc and, therefore, reduces the risk of death.

Szczerbiński (2003) raises three points with regard to the proposed models to date. Firstly, there may be an overestimation in the critical danger energy. Secondly, flashover is an exceptional case, rather then the normal. Finally, the ratio of dead victims to injured victims is overestimated.

Flashover can be accountable for the burn marks and vaporisation of jewellery. The surface flashover will occur within microseconds of the flash, and will contain most of the current, however, as long as the arc is maintained, there can be as much as 5 amperes flowing through the body cavity for a couple of milliseconds. This current, if directed through the heart, or part of the nervous system, can cause cardiac or respiratory arrest, or both (Rakov & Uman (2003)). What is now termed the ‘fifth mechanism of lightning injury’ can also result in a few hundred amperes flowing through the body for several tens of microseconds.

All experiments performed on animals did not indicate the cardiac cycle in their analysis. Therefore, the limits presented may be in reference to the upper limit required to cause death, regardless of the position in the heart cycle. If the heart is in the T wave section, then the value required is significantly less.

It is thought that the majority of the internal current flow is through ionic fluid, which would be in media such as blood, cerebrospinal fluid or similar (Cooray (2003)). Andrews highlights again that, after this, muscle would be the next most conductive material in the body, all the way up to bone. It is thought that, as a result of myelin, nerve tissue is made inaccessible and, therefore, an unlikely medium for current flow.

Kitagawa also defines that the electric field intensity required for flashover to occur over a person is approximately half that of air. This would thus reduce the initial amount of current flowing through the human body before flashover occurs, but does not limit the potential developed once the arc occurs and, therefore, the current flowing through the body. Kitagawa also emphasises the following; firstly, the presence of jewellery on the body may aid in providing surface conductive paths, therefore increasing the chances of a surface flashover, thereby reducing the chance of a fatal internal current. Secondly, the jewellery does not increase the chances of being struck, this is influenced by the physical presence of the person. The only enhancements come when an object protrudes higher than the person, such as an umbrella, golf club or fishing rod.

The reported mechanism of death is often incorrect as the recall of a witness is often uncertain, and cannot always be relied on to provide confirmation of a direct lightning strike to a victim. Forensic pathology provides insight into whether the event was a direct strike to the victim. Only 3 to 5 % of cases reported are as a result of direct attachment to a victim. The value is similar for touch potentials, but then dramatically increases for side flash, which is in the vicinity of 30 to 35 %, and up to 50 to 55 % for step potentials. The so called fifth mechanism of lightning death, Anderson *et al.* (2002) the upward streamer, accounts for approximately 10 to 15 %. This highlights two major areas of concern, these being the step potential and side flash. If these mechanisms can be protected against, then the number of fatalities should decrease.

4.7 Summary

In this chapter, the human body impedance model has been presented. This, in conjunction with computer models, is used in simulations to determine what interaction lightning currents will have with the human body. Tests performed on animals provided insight into lethal energy limits that the body can withstand, and this is defined as 62.6 J/kg. However, this has been questioned, and the feeling is that this value could be anywhere between 10 and 50 J. The mechanisms of lightning injury have also been presented, and these scenarios, in conjunction with the current paths through the body, dictate the possible injuries or, in the worst case, death. An understanding of the electrical properties of the body exist, and this aids in defining the probable current paths through the body. However, absolute certainty does not exist, and further work in this area is still required. Ethics and moral issues limit the progress of such work. Neurological effects, as a result of lightning strike, appear in many victims and can last for a short time, or be permanent.

A good understanding of the interaction of lightning with ground-based objects, and the dissipation of lightning in the ground is well described. With this knowledge and strict codes surrounding the construction of sports stadiums, measures could easily be put in place using the existing material, that could make these facilities safer. It may be possible to use the existing understanding of the physics of lightning and objects, to provide an understanding of the lightning dangers in these facilities. With this knowledge, corrective actions can be put in place to reduce the risk and thereby reduce lightning related incidents.

A collection of case studies, performed by a number of researchers from the engineering, medical and health science fields have been discussed. The findings, though in line with their respective research fields, highlight the number of different parameters associated with an event, as well as the fact that no two cases are the same. Varying information and data with few similarities, means the development of a generic model is difficult. The only certainty is that outdoor recreation activities do place living beings at a greater risk to lightning incidents. However, many of these dangerous environments are known and some measure of risk aversion control could be put in place to reduce the number of adverse incidents. This may come in the form of early warning systems, lightning protection measures, or some form of education of those in charge, to make sure areas are cleared well before time.

In the next chapter, risk, its definitions, and current applications are presented. Modern society provides a plethora of information on all aspects of one's life. With this, increased awareness and safety concerns are raised. Risk assessments have become the norm and dictate what could or should be done. The international lightning risk standards are presented and results of their application are discussed.

Chapter 5

Risk

In this chapter, the concepts of risk are presented. Traditional risk assessment methods, such as the realist perspective, are considered alongside those of the sociocultural perspective. Lupton (1999) describes the fact that risk has become an increasingly pervasive concept in modern society. Every action or decision has some associated risk attached. Means of quantifying the risk can be difficult, and the results of risk assessments are often unclear and have little meaning. International standards provide the best available means of determining the risk associated with lightning to living beings. The current lightning risk standards are discussed and observations in their application are presented.

5.1 What is risk?

Risk is derived from two schools of thought. The first is the realist, or cognitive science, perspective, which is approached using natural scientific objectivism about hazards. The second is derived from the sociocultural perspective, which is based on cultural relativism about hazards. Anthony Gidden states "*It is a society increasingly preoccupied with the future (and also with safety) which operates the notion of risk*", (1998). Gidden, within his writing, refers to the necessity for an individual to be able to trust. Without this, the belief in the work pertaining to risk and quantifying it, becomes very difficult. It is also important, therefore, for the individual to be able to question the process used in understanding the risks being presented (Lupton (1999)). Aven (2011) has the following thought about risk:

> "*The ultimate goal of risk communication is to assist stakeholders and the public at large in understanding the rationale of risk-informed decisions, and to arrive at a balanced judgement that reflects the factual evidence about the matter at hand in relation to their own interests and values (Aven and Renn, 2011).*"

This would indicate that risk is a double edged sword, and requires elements from the realist perspective, as well as the sociocultural perspective, to truly have any meaning or acceptance. A sociologist, Ulrich Beck, when discussing the understanding of risk by society, stated (Lupton (1999)); *"Neither experiments nor mathematical models can 'prove' what human beings are to accept, nor can risk calculations in any way be formulated solely in technological-bureaucratic terms, for they presuppose the cultural acceptance they are supposed to manufacture."*

5.2 Defining risk

Risk has been redefined over the last few centuries, initially pertaining to maritime exploration or maritime insurance, or matters that were as a result of an act of God and, therefore, excluded the idea of human fault and responsibility (Lupton (1999)).

Risk is defined in the Collins concise English dictionary as; "*The possibility of incurring misfortune or loss; Hazard; To expose to danger or loss".* Probability is also used in conjunction with risk definition and, from a statistical point of view, is defined as; "*A measure or estimate of the degree of confidence one may have in the occurrence of an event, measured on a scale from zero (impossibility) to one (certainty)".* These are broad based definitions and, as a result, different disciplines include different components in defining this, including; probabilities, uncertainties, and expected values. However, there seems to be no uniformity in the descriptions and processes (Aven (2011)). The following list shows various definitions used to describe risk:

- Risk equals the expected loss, Verner and Verter - 2007 and Willis 2007.
- Risk is the measure of the probability and severity of adverse effects - Lowrance 1976.
- Risk is the combination of probability and extent of consequences - Ale 2002.

- Risk is equal to the triplet $(s_i,\ p_i,\ c_i)$ where s_i is the i^{th} scenario, p_i is the probability of that scenario , and c_i is the consequence of the i^{th} scenario, $i =$ 1,2,3...N - Kaplan and Garrick 1981.
- Risk refers to the uncertainty of outcome, of actions and events - Cabinet Office 2002.
- Risk is a situation or event where something of human value (including humans themselves) is at stake and where the outcome is uncertain - Rosa 1998 and 2003.
- Risk is an uncertain consequence of an event or an activity with respect to something that humans value - International Risk Governance Council (IRGC) 2005.
- Risk is equal to the two-dimensional combination of events/consequences and associated uncertainties - Aven 2007 and 2010.
- Risk is uncertainty about the severity of the consequences (or outcomes) of an activity with respect to something that humans value - Aven and Renn 2009.
- The value of probable average annual loss (humans and goods) due to lightning, relative to the total value (humans and goods) of the object to be protected, IEC 62305-2 (IEC (2007*c*)).

In the same manner, there are multiple definitions for probability, of which some of the commonly used definitions are (Aven (2011)):

- A probability is defined as a relative frequency P_f: the relative fraction of times the event occurs if the situation analysed were hypothetically"repeated" an infinite number of times; P_f is referred to as a frequentist probability. It can be understood as a parameter of a probability model.
- Probability P is a subjective measure of uncertainty about future events and consequences, seen through the eyes of the assessor and based on some background information and knowledge (the Bayesian perspective). The probability is referred to as a subjective or knowledge-based probability.

Instead of using the term Probability (P) this can be exchanged to the term uncertainty (U).

The sociocultural perspective is based less on the collection of data for the analysis of risk. This perspective has come about from disciplines such as cultural anthropology, philosophy, social history and cultural geography. The concept of removing the notion of risk from the individual because they do not understand, is a misconception. Many can produce a reasonable argument regarding the probabilities of risk, however, their sway has more to do with their culturally learned assumption. This is an argument put forward by Douglas in 1992. Douglas goes on to argue that education is not necessarily the best way to resolve risk disputes, but that the collapse of the transfer of thought process is as a result of political, moral and aesthetic judgements on risk (Lupton (1999)). The greatest problem here, is that creating a generic risk model becomes very difficult when trying to incorporate all social aspects from different societies.

5.3 Risk types

Lupton (1999) states that there are 6 major categories of risk, which are:

- Environmental
- Lifestyle
- Medical
- Interpersonal
- Economic
- Criminal

she goes on to state:

> *"Risk has become an increasingly pervasive concept of human existence in western societies; risk is a central aspect of human subjectivity; risk is seen as something that can be managed through human intervention; and risk is associated with notions of choice, responsibility and blame."*

As can be seen from the list of risk types, this encompasses all aspects of an individual's life. The influence of each type of risk will heavily depend on their relative position in society. However, in most cases, the notion of blame has, in many respects, been shifted out of the sphere of influence of the individual. This has primarily come about, because of unfavourable situations, to remove the responsibility from the individual.

An example would be the thought that obesity in much of the world today, is as a result of fast food distributors. They may provide the means, but the choice is still up to the individual. Beck (Lupton (1999)) states that the usual response to grave dangers is to deny their existence, as a kind of psychological self-protective mechanism, an attempt to maintain a sense of normality.

The process of risk analysis, or the notion of probabilities, has led to development of different approaches, which include methods on possibility theory and evidence theory. Aven (2011) poses the question, how can we guarantee accurate risk estimates? This depends on the intention of the risk analysis process; is risk more about identifying the uncertainty description than accurate estimation?

5.4 Risk methods

Cumming (2006) defines that risk assessment or analysis is a scientific activity, but it is not scientific *per se*. Risk assessment cannot demand the certainty and completeness of science. Risk is an important activity, it depends on science and has an important stake in receiving the input of good science. Weinberg states (Aven (2011))- *"Experimental observation, is inapplicable to the estimation of overall risk in the case of rare events, which are those instances where public policy most often demands assessment of risk."*

The methodologies for the formulation of risk will be presented in *Section 5.5.* Probability theory is traditionally based on three axioms:

1. A probability is a non-negative number
2. The probability of a certain event is 1
3. The probability of a union of mutually exclusive events is equal to the sum of probabilities of each event.

Though the theory and application of risk analysis methods are often placed on a non-scientific platform, it can be concluded, with the modern understanding of both mathematical principles and the physical world, that sufficient scientific parameters are available to make the near scientific method of risk analysis valid in understanding common place uncertain events.

5.5 Theorising risk

A risk assessment is a methodology designed to determine the nature and extent of risk, i.e. assess the risk (A,C,U). It comprises the following main steps (Aven (2011)):

1. identification of hazards/threats/opportunities (sources)
2. cause and consequence analysis, including analysis of vulnerabilities
3. risk description, using probabilities and expected values
4. identification and assessments of uncertainty factors
5. risk evaluations, i.e. comparisons with possible risk tolerability (acceptance criteria)

Risk description by Aven:

$$Risk\,description = (A, C, U, P, K) \tag{5.1}$$

where

A = Event
C = Consequence
U = Uncertainties not captured by P
P = Knowledge based probabilities
K = Background knowledge upon which U and P are based

Equation 5.1 describes a knowledge based risk calculation that encompasses concepts of uncertainties not captured by the probabilities, and a background knowledge of the probabilities and uncertainties. However, even in knowing and understanding some of these parameters, it is difficult to define a risk that is all encompassing. The limitation of the risk assessment model needs to be carefully defined and presented to the user.

$$Risk = (A, C, P_f) \tag{5.2}$$

where

A = The events or scenarios
C = The consequences of A
P_f = Relative frequency-interpreted probability

The interpretation of probabilities can fall into two categories. Firstly, where probabilities are interpreted as relative frequencies, secondly, where probabilities are subjective (knowledge-based) probabilities, where the expected value is interpreted as the centre of gravity of the probability distribution. A second description for risk is shown in *Equation 5.2*. At the end of the process, there are two criteria of the risk assessment that need to be met, these are reliability and validity (Aven (2011)).

5.6 Lightning risk standards

An early form of lightning risk assessment for a structure, to determine the necessity for protection measures was defined as (Spilkin (1973)):

$$Risk = \frac{A \times B \times C \times D \times E}{F} \tag{5.3}$$

Where:

Index A - Type of structure; ranging from (1) for a metal mast or chimney, domestic dwelling to (10) for an explosives building, lighthouse or airport control tower.

Index B - Walls; categorised by the roof type, and then the material of the wall, being timber, metallic, non-metallic.

Index C - Exposure; where a small building in a built up area has an index of (1) , through to (4) for a building in bare open country and standing at least 15 m higher then surrounding structures.

Index D - Situation; (1) indicates that the structure is located on flat ground, up to (3) for hilltop or mountain top.

Index E - Contents or consequential effects; (0) representing the situation where protection is not justified from occupancy or contents perspective, through to (6) for explosives or historic contents.

Index F - Lightning prevalence; geographical location of the structure from Cape Town (20) to Kimberly, Windhoek. Bloemfontein, Pretoria and Johannesburg (1).

The results of the assessment were compared to the values shown in *Table 5.1*, and protection measures would be adopted accordingly.

Table 5.1: Table for the assessment of lightning risk to structures, used by the SABS in the 1970s (Spilkin (1973)).

Risk	**Assessment**	**Protection**
0 - 1	No risk	Not needed
1 - 4	Small	Not needed
4 - 9	Fair	Might be advisable
9 - 16	Medium	Advisable
16 - 25	Great	Strongly advisable
over 25	Essential	Should be compulsory

South Africa, and many other countries, adopt the lightning standards produced by the International Electrotechnical Committee (IEC), in their entirety. A few countries opt to adopt certain sections of the IEC standards and rewrite those sections that are relevant to their country. These include the USA, which integrates the lighting standards into the National Fire Protection Act (NFPA), where the lightning risk can be found in section 780. Australia and New Zealand re-write the standards into their own standard, such as AUS/NZ 1768(int):2003 lightning protection. This document is compiled using references from IEC 61024, 61312, 61663 and 61662. Contractual agreement on using the standard makes it compulsory for contractors to comply with all aspects, as agreed upon with a client.

In 2006, the IEC released a new suite of standards with respect to lightning protection (IEC (2007*b*,*c*,*d*,*e*)). Part 1 provides the details surrounding the general principles of lightning parameters, cause of damage, and basic methods of protection. Part 3 and 4 look at more in-depth requirements for the protection from lightning of structures and equipment respectively. The standard of interest for this work is Part 2: Risk management IEC (2007*c*). This part is applicable for the assessment of a structure or a service, due to lightning flashes to earth IEC (2007*c*).

5.6.1 Risk process defined by the IEC standard

The risk analysis process used in the IEC standards is best described as the realist perspective. The standards define the risk with the following generic equation:

$$R = NLP \tag{5.4}$$

where

R = The value of probable average annual loss $[yr^{-1}]$
N = The number of dangerous events per annum
P = The probability of damage to a structure
L = The consequent loss

The total risk being calculated, relating to a type of loss, is comprised of a number of risk components, which are summed together. Each component relates to a different source of damage. This refers to the mechanism by which lightning will enter the structure and the potential loss as a result of this event. The sources of damage include, direct and indirect strikes to a structure as well as direct and indirect strikes to a service.

The types of risk, based on the average probable loss within a structure, are defined as IEC (2007*c*):

- Risk of loss of life - R_1
- Risk of loss of service to the public - R_2
- Risk of loss of cultural heritage - R_3
- Risk of loss of economic value - R_4

Appendix B Defines the equations to determine the risk types 1 and 4. In addition equations are defined which can be used to determine the potential saving with and without protection measures in place. From work performed using these two equations (results shown in *Appendix B*) the following points need to be considered. A simplified risk assessment can be performed, which will provide a useful initial assessment. However, a full assessment requires extensive information about the structure and the services connected to the structure. This information needs to include knowledge of the presence of living beings during dangerous events. In the case of a residential structure this is a very difficult value to determine. For each assessment the risk type is calculated and then compared to the tolerable risk. If the total risk is less than the tolerable risk, it is considered that the risk is significantly small enough, then protection measures are not required. However, if it is greater than the tolerable risk, protection measures should be installed, but this is still at the discretion of the owner of the structure in many countries, including South Africa.

Performing risk assessments of three types of structures typically found in South Africa, there were certain factors in the risk assessment which caused significant changes to the results if the factor was slightly altered. This would often shift the results of a risk assessment for a structure from being less than the tolerable risk to being well above it. These factors include:

- Service
    - Length (L_c)
    - Height (H_c)
- Lightning ground flash density (N_g)
- Soil resistivity (ρ)
- Risk of fire (r_f)
- Probability of failure of installed SPDs (P_{SPD})
- Relative location (C_d)

The risk of fire factor (r_f), which is based on predefined values of the specific fire load for the structure is of concern. This factor is defined as the ratio of the energy of the total amount of combustible material in a structure and the overall surface of the structure IEC (2007*c*). In the case of a high fire risk, the specific fire load should be greater than 800 MJ/m^2. The process of determining this for a normal residential structure is quite complex. This is because the energy content of common household items, is not generally known. There are no available look up tables or lists providing this information. The concern with this is the effect the fire risk factor has on the calculation for the total risk. The total risk changes by an order of magnitude for the different fire risk levels. The IEC 62305-2 analysis limits the risk assessment to a maximum distance of 3 metres outside a structure, for all risk types.

Tolerable risk

Once an assessment has been performed, the total risk can be compared to the tolerable risk values as defined by the IEC.

Table 5.2: The tolerable risk values, R_T, as defined by the IEC 62305-2 (IEC (2007*c*)).

Type of loss	$R_T(y^{-1})$
Loss of human life or permanent injury	10^{-5}
Loss of service to the public	10^{-3}
Loss of cultural heritage	10^{-3}

If the risk is calculated to be less than the tolerable risk, no protection measures are required. If the result is greater than the tolerable risk, it is recommended that protection measures should be put in place. A design using various lightning protection measures is developed and the risk analysis is recalculated to determine if the protection measures do in fact reduce the risk to below the tolerable risk level. If this is the case, then it is recommended that the protection measures should be put in place. The interpretation of the tolerable risk for the loss of life is a difficult quantity to comprehend, when related to the average life expectancy. The tolerable risk can be rewritten, and is interpreted as 1 in 100 000 man years. This would mean that if 100 000 people were located in a dangerous situation for 1 year, then it would be acceptable if 1 of them were to die as a result of lightning. Interpreting this in another way, would be to say that 10 deaths per million people per year is an acceptable loss.

These values have been decided by international committees, which have worked to provide the best available recommendations and advice for engineers and the general public. One question still begs to be asked, should any deaths as a result of lightning be acceptable? It may be difficult to prevent individuals from walking in potentially dangerous situations, but, as discussed in *Chapter 2, 4* and *Appendix A*, most lightning incidents occur in organised outdoor activities.

5.7 Summary

The concept of risk and how it is becoming an increasingly pervasive concept in our daily lives is presented. The notion of responsibility and blame appears to be moving away from the individual and applied to other entities. As a result of this, there is an increasing necessity for these entities to provide means of warning and protecting any living beings within their confines. This requires assessments of the risk of lightning to different facilities and the application of protection measures.

Current risk analysis methods use the realist perspective which is defined as the probability of an adverse event resulting in a consequential loss. However, as many lightning related incidents occur in an outdoor environment, it may be necessary to consider that social parameters should possibly be included when performing lightning risk assessments.

The IEC 62305-2 provides a means of determining the lightning risk for four risk types. Assessments have been conducted for risk type R_1 (loss of life) and R_4 (loss of economic value). For a typical urban residential structure the assessments appear to hold validity. However, in the case of alternate residential structures, the assessments are usually greater than the tolerable risk, indicating the requirement for some form of protection. Due to the nature of these structures, certain factors, such as the risk of fire, have a great influence on the result. There are a number of these factors in the risk assessment process, which need to be carefully considered, as to their validity in this process. The risk assessments, particularly with reference to the loss of life, can only be determined up to 3 m outside a structure. However, many of the recorded lightning incidents have occurred outdoors, usually associated with a recreational activity. Therefore, it is clear that some method to determine lightning risks in such environments is required.

The influence of parameters such as the risk of fire, and service length and height, have a considerable influence when calculating the risk of loss of life within a structure. Without an in-depth knowledge of the structure and its associated services, the results are interesting but hold little bearing on the actual dangers, and therefore, hold little value. These values have been developed by international committees, but uncertainties surrounding the probability and loss factors mean the results can always be questioned. Misunderstanding or the incorrect application of these factors can result, in the calculated lightning risk, being severely skewed in relation to the tolerable risk. The results therefore, when presented to lay people, provides little meaning or value in making decisions, and therefore calls into question the validity of the process.

In the following chapter, the *Action Volume Ratio* is presented. This is a method that has been developed to determine the dangers of lightning to living beings in any defined volume.

Chapter 6

Action Volume Ratio - AVR

In this chapter, the Action Volume Ratio (AVR), is proposed as a new method for determining the danger of lightning to living beings for any volume. This method applies the engineering principles used in understanding how lightning interacts with grounded objects, to determine the potential dangerous areas for living beings in both structures and open spaces. The AVR method can be combined with lightning ground flash density data to provide incidence and frequency values. It can also be presented numerically and visually, which provides a useful tool to present the dangers associated with lightning to engineers and lay people alike. The previous chapter explored conventional risk analysis methods, however, it will be shown that these methods have limited significance for defining risk in outdoor environments. The Median Lethal Limit (MLL) was first developed through forensic investigations of lightning scenes, which will be discussed further in *Chapter 7*, to define a two dimensional lightning danger representation for any given outdoor environment. This method is further expanded to provide a means of defining the danger of lightning to living beings in any given volume (AVR), and will be shown in a number of examples.

> "*Whose fault? is the first question. Then, what action? Which means, what damages? what compensation? what restitution? and the preventive action is to improve the coding of risk in the domain which has turned out to be inadequately covered. Under the banner of risk reduction, a new blaming system has replaced the former combination of moralistic condemning the victim and opportunistic condemning the victim's incompetence*" - Douglas (Lupton (1999))

6.1 Lightning risk in open spaces

The IEC 62305-2 *Risk management* document provides a tool to determine the risk of lightning within a structure and up to 3 m outside it. The total risk, for four different risk types is presented in the standards. However, in this work, consideration has only been given to risk type R_1, the risk of loss of life. There are no existing methods in the current standards for determining the risk of lightning in open spaces. It may be considered that this is a pointless exercise as the dangers are inherent, yet, as shown in *Chapter 2, 4* and *Appendix A*, most lightning injuries and fatalities occur outdoors. The reason for this comes down to three possibilities:

1. Socio-economics places many people at risk, particularly those in third world countries.
2. Lack of education, where decisions are based on common myths and misconceptions regarding lightning and personal safety.
3. Educated people, who are aware of the risks, but deem the probability to be small enough that precautionary actions are unnecessary.

In addition, as stated in *Chapter 5*, the notion of risk and responsibility is being shifted away from the individual. Therefore, organisations and corporations need to guard against situations where blame can be shifted onto them instead. Significant economic losses, particularly with respect to livestock, could be mitigated by identifying the inherent risks and taking measures to provide protection. There is a need to develop a method to adequately define the lightning risks or dangers inherent in open spaces.

6.2 Development of a risk model for open spaces

The development of the risk analysis process for open spaces uses the form of the realist perspective, requiring the number of expected annual events (N), probability (P), and the associated losses (L). The following list of factors needs to be considered when creating a risk analysis method for open spaces. How these are applied, and the parameters required in calculating the risk, is presented in the next section.

- Peak return stroke current
- Lightning ground flash density
- Soil resistivity
- Type of living being
- Physiology of living being
- Contact points
- Orientation of living being
- Tree type
- Moisture of surroundings
- Surface arcs

6.2.1 Considerations in developing a risk model for open spaces

The number of expected events is a relationship of the area of the space being assessed, in combination with the expected ground flash density. As knowledge increases through the installation of Lightning Detection Networks (LDN), this value becomes more accurate. The assessment is for open spaces. Therefore, the influence of surrounding objects, such as buildings and their relative location, are not initially considered, as required by the IEC 62305-2 weighting factors. Consequently, the relationship is the ground flash density multiplied by the area being assessed, in kilometres squared. Assuming an N_g of 8 flashes/km^2/year, and an area of $200\,\text{m} \times 200\,\text{m}$, the expected number of events would be 0.32 strikes per year, or 1 strike every 3.125 years.

Considerations for the probability and the associated loss are based on the different injury mechanisms. The probability factors are dependent on the environmental parameters and the location, orientation and physiology of a living being in the space. The type of living being also greatly affects the potential for a loss. By looking at a number of different living being parameters, can a risk analysis method be applied to any real world situation. Or are multiple methods, based on different living being physiologies, required in order to fully define the lightning risk for an area.

In an open space, the magnitude of the peak return stroke current is critical in determining the probability of a loss. Therefore, for any risk process, this value needs to be defined first. If an assessment of the area is to be performed using a method such as a *Monte Carlo Simulation*[1], the probability distribution function for negative return stroke currents can be used. Alternatively, an analysis can be performed using the median current value of 20 kA, as defined in the IEC 62305-1. Using *Equations 4.4* and *4.3*, defined in *Chapter 4*, in conjunction with the lightning peak current, the most probable ways in which a lightning strike could interact with a living being can

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[1] A statistical method used to assess risk scenarios using a defined set of random samples.

be investigated. From this, probabilities can be assigned to different mechanisms and, therefore, the losses can be determined.

The conditions at the time of strike are important. Whether the strike occurs at the beginning of, during, or after, the storm, will have an effect on the path taken by the lightning. For the purpose of this discussion, the object assumed to be struck will be a tree, unless otherwise stated. If the strike occurs at the beginning of the storm, the object may conduct the current internally, resulting in partial or total destruction, which increases the chance of blunt trauma to a living being in the area. If rain is already falling, this will aid in the current path being on the outside of the object, reducing the probability of destruction of the object. The rain, however, will lower the electric field strength, increasing the distance a side flash can travel, therefore increasing the chance of attaching to a living being in the space. The presence of water on the ground may also increase the chances of surface arcs, which can contain a significant percentage of the peak current. The advantage of the presence of rain is that the soil resistivity may be reduced, as a result decreasing the earth resistivity which, in turn, reduces the distance and magnitude of developed step potentials. The parameter of the object will also influence the dissipation of the currents to the ground. A tree with a deep tap root, versus superficial radially spread root system, will affect the dissipation of the current into the ground.

The location of a living being in the space is important in order to determine the expected losses. In returning to using a *Monte Carlo Simulation*, the living being can be placed randomly anywhere within the space. This would provide a statistical answer to the probability of a lightning event interacting with a living being. However, in the examples of lightning injuries described in *Chapter 2* and *4*, the majority of events occur near some object. This means that there needs to be a bias, in any calculation, towards a living being located near to, or under, an object in the space. If common use of the space by living beings is known, it may be prudent to apply weighting factors to certain objects in the area. As an example, if a pathway is commonly used through the area, a nearby tree may be used more often to provide shelter during a storm then any other tree in the vicinity, thus posing a greater danger to living beings during a thunderstorm. The type of living being is also important when attempting to determine the probability of losses in the assessment. A quadruped is considered to be far more susceptible to lightning strikes as, in most cases, the current paths would involve the thorax resulting in an interaction of the current with the heart.

The orientation and position of the living being is critical. In the case of quadrupeds, the orientation is less important as the step length between both the anterior and posterior limbs, or between the left and right hand side, can result in currents flowing through the thorax. In the case of human beings, a larger step potential would occur if the person is walking versus standing still. The orientation of the person, with respect to the point of strike, will also influence the probability of a dangerous step potential. Whether a living being is sitting or lying down will affect the outcome of an event. A person's position also affects the risk associated with side flash, as this is a function of height. Therefore, the potential developed at a height of 2 m is greater than that at 1 m.

The physiology of the living being is also important, with particular reference to human beings. The gender, height, weight and age, all have an effect on what result an injury mechanism may have. These parameters will affect internal body impedances, contact impedances, step length, and the potential developed with respect to side flashes. Should all these parameters be considered, or is the separation between biped and quadruped sufficient for an analysis?

The current path and energy absorption of the body of a living being is important in understanding the expected losses. Kitagawa's work indicated that the threshold for death is 62.6 ,J/kg (Kitagawa *et al.* (1973)); however, there has been disagreement on this value. Alternatively, Cwinn & Cantrill (1985) indicated that currents as low as 0.75 mA could result in a fatality; admittedly this is in relation to power frequencies. The current path is also critical, but, as described in the standards, is a heart factor a valid method to determine the probability of a fatality in a risk analysis process? Returning to the moment of the analysis, if an event occurs during or after the storm, the living being may be wet, which would increase the chance of external flashover occurring and therefore the probability of survival of the living being increases.

It has been shown that there are a number of different parameters that will affect both the probability of an event occurring as well as the possible losses. These factors will be considered in the development of a risk analysis method for open spaces in the following section.

6.2.2 Development of a risk analysis method for an open space

Using the consideration highlighted in *Section 6.2.1*, the construction of a risk analysis method will now be described:

1. The probability of a person and a lightning strike coinciding at the same place is $1/Area \times 1/Area$.
    (a) The result is multiplied by the ground flash density for the area being considered, $N_g/Area$.
2. Assuming a flat open field, with no other object in it, except a human. The area considered has a ground flash density of 9 flashes/km^2/year. The space being considered is an area 120 m by 80 m. This is a total area of $9.6 \times 10^{-3}\,km^2$, therefore the risk of a direct strike is calculated to be 9.375×10^{-10}.
    (a) In addition to this, the presence of rain is considered. This includes an additional probability factor of 1/2, which reduces the risk to 4.688×10^{-10}.

This indicates that the probability of a direct strike to a person in a limited area, as described, has a very small chance of ever happening. The inclusion of other risk parameters is obviously required, however, the variation of result obtained would be minimal.

If the same process is considered for an indirect strike, the dangerous area would increase. However, this is based on the probability distribution for a lightning stroke. Therefore, the initial part of this analysis is already based on a statistical probability, which would be initially skewed. Regardless of this fact, the procedure continues with the following parameters:

- A peak return stroke magnitude of 15 kA
- An earth resistivity of $300\,\Omega m$
- Lethal current of 2.5 A
- A step length of 1 m
- A body impedance of 800 Ω

A lethal current can be achieved up to a distance of 19 m away from the point of strike. Therefore, the probability of the person encountering a lethal step potential is now $1/Area \times A_{lethal}/Area \approx 1.2 \times 10^{-5}$. This is calculated in the same manner with the lightning ground flash density. Weighting factors with respect to the presence of rain, the location of the living being, and the physiology and orientation of the living being, need to be considered. None of these can be accurately quantified, therefore a solution is possible but has little meaning. Additional factors may need to be considered from a socio-cultural perspective, as the probabilities of living beings being located in outdoor spaces and in dangerous locations would increase in third world countries, as the size of the rural population is considerably higher.

6.3 Development of the Action Volume Ratio

The ability to describe and quantify the risk of lightning to the general populous is difficult. The calculated risks are so misunderstood that the results are meaningless and hold little value to the man in the street. The international standards, as mentioned, provide a means to calculate the risk within a relatively controlled environment, that of a structure. Nevertheless, in most cases, the greatest concern is whether or not the electronic equipment in the structure will survive the next thunderstorm season. As has previously been described, most lightning incidents occur outdoors and in many cases the number of fatalities is only a fraction of the number of injuries. In most cases these injuries have a significant impact on the life of a living being long after the actual event. The calculation of the lightning risk in an outdoor environment has a significant number of factors, as previously described. The determination of a total risk method would need to be performed for a number of different factors, making the process unnecessarily cumbersome.

Through a number of lightning incident investigations in open spaces, it became clear that a means to better quantify the risk was required. The existing processes could not be applied and therefore an alternate method was developed. This new methodology is described as the Median Lethal Limit (MLL), which is presented in *Section 6.3.1.* The Action Volume Ratio (AVR) was borne out of the MLL method as it was considered that the process could be applied to any given volume, and not only be limited to outdoor areas. This will be further explored in *Section 6.4*.

6.3.1 Median Lethal Limit method

The MLL derives its name from the median peak current value for the probability distribution function of a lightning negative return stroke. This value is considered in the literature to be 20 kA (IEC (2007*b*)). This, in combination with the six known lightning injury mechanisms which were described in *Section 4.3*, form the basis for the MLL method. By applying the median lightning return stroke current to each of these injury mechanisms, a danger area can be determined. The union[2] of these danger areas is then divided by the total area, to provide a total danger ratio for the area under analysis. *Equations 6.1* and *6.2* were developed to represent the application of the MLL method.

Consideration needs to be given to the three injury mechanisms: direct strike, upward streamer and barotrauma. These are all injury mechanisms that need a living being to be in close proximity to the lightning channel. As these are inherent dangers for any open area, these injury mechanisms are excluded from this risk analysis method. Any location in an open area has the same probability as any other for a direct strike, barotrauma or upward streamer to occur. It is primarily a statistical probability, based solely on the lightning ground flash density, size of the area being analysed and the location of the living being in the space. *Equation 6.1* defines the dangers for an open space for these three injury mechanisms. The process of a living being seeking a form of shelter will also significantly reduce the chance of a direct strike or the initiation of an upward streamer or barotrauma. However, this action now increases the chance of a side flash, touch or step potentials occurring.

With regard to the lethal limit of a developed step potential, the step length and lethal current taken into account need to be stated. The lethal current is still considered an unknown factor in the analysis, however, a range from a few milliamps to a few amps can be assumed. For quadrupeds, this is a considerably lower than for that of a biped. However, this is an assumption as the lethal levels of step currents cannot be fully quantified. In any analysis, the greatest influence to the MLL will be from the development of step potentials, then a side flash and, finally, touch potentials. The MLL based on these three injury mechanisms is described by *Equation 6.2.* As the parameters of the space change, the contribution of each of these injury mechanism areas to the total dangerous area would change. The results can be multiplied by the expected ground flash density for the space being analysed. This provides an incidence or frequency of expected events resulting in a dangerous event for the space. Confining parameters for the application of the MLL method are as follows:

- The space is considered to have a homogeneous lightning ground flash density
- The space is considered to have a homogeneous earth resistivity
- An object in the space is considered to be inanimate

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[2] As in mathematical set theory, the union of two sets A and B is the collection of points which are in A or in B (or in both): $\mathrm{A} \cup B = \{x : x \in A \quad \text{or} \quad x \in B\}$

- Any object within the space will enhance the electric field, therefore, any object is a preferential point of strike

$$\text{iff} \quad \Omega \in \emptyset \quad : \quad MML = 1 \tag{6.1}$$

$$\text{iff} \quad \Omega \in [object] \quad : \quad MLL = \frac{A_{touch} \cup A_{side\,flash} \cup A_{step\,potential}}{A_{\Omega}} \tag{6.2}$$

Each lethal area is dependent on certain electrical parameters of the space. For determining the area associated with a step potential, the relationship is:

$$A_{step\,potential} \equiv f(I_{mp}, Z_g, Z_b, l_{step}) \tag{6.3}$$

where

I_{mp} = Median peak return stroke current [kA]

Z_g = Earth impedance [ρ m]

Z_b = Impedance of the living being in the space [Ω]

l_{step} = Step length [m]

The same process can be applied for a touch potential and side flash, based on the area being assessed. The parameters may include the impedances of the objects in the area, the critical parameters of the living being, such as height and internal impedance and contact resistance as well as the distance from the struck object. However, these would be dependent on the site under investigation.

Application of the MLL to a space

To demonstrate the MLL method, an example for the application of the method is presented. The space to be analysed is a 600 m × 600 m flat area, with 9 objects (trees). The median peak return stroke current is 20 kA. The impedance of a living being's body is assumed to be 1 000 Ω. Three current levels are used as examples and are each applied to three cases of different soil resistivities. Currents of 0.5 A, 1 A and 4 A used for this analysis could all potentially result in an injury or even death. In order for these currents to occur, step voltages of 500 V, 1 kV and 4 kV are required, if a step length of 1 m is assumed.

The graph in *Figure 4.7*, can be used to determine the distance from the point of strike that would result in the currents described above. The lethal distances for each case is shown in *Table 6.1.*

Table 6.1: Table of the distance from the point of strike, indicating the lethal limit for a specific current and earth resistivity

Description	**Developed body current**		
	0.5 A	1 A	4 A
Case 1 - 100 Ωm	25 m	18 m	9 m
Case 2 - 500 Ωm	56 m	39 m	19 m
Case 3 - 1000 Ωm	78 m	55 m	28 m

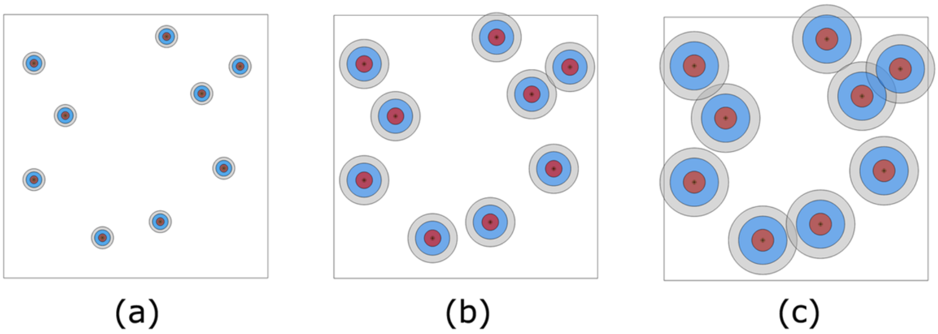

Figure 6.1: Each figure has a different soil resistivity defined as: (a) $\rho = 100\,\Omega m$; (b) $\rho = 500\,\Omega m$ and (c) $\rho = 1\,000\,\Omega m$. The circles define MLL areas for the different lethal currents: 0,5 A - grey; 1 A - blue; 4 A - red.

The distances for the different current levels are used to calculate the dangerous area for each object. These areas are graphically represented in *Figure 6.1*. The circle, shaded grey, represents an expected current through a living being of 0.5 A, the blue is for a current of 1 A, and the red is for 4 A. *Table 6.2* shows the results for the total dangerous area - the MLL ratio. In addition, the ground flash density (N_g) for the space can provide additional information, in the form of incidence and frequency (yrs). For the space being analysed, the effective ground flash density is 2.88 flashes/km^2/year.

The MLL ratio and the frequency are the results that provide the most meaning to the description of the lightning dangers within the space. The ratio is a percentage of the dangerous area to the total area. The frequency indicates the number of expected events that would occur in the space in a given time frame. Case 3 shows that a 0.5 A current would be developed once a year. Whereas, in case 1 a 4.0 A would only occur once every 54 years. This example also shows that by installing lightning protection measures the MLL ratio would decrease. Reducing the soil resistivity directly affects

Table 6.2: MLL results for all earth resistivity cases defined for the space.

Description	**Area** (m^2)	**Ratio -** $\frac{A_{lethal}}{A_{Total}}$	**Incidence,** $N_g = 8$	**Frequency** (yrs)
Case 1 - 0.5 A	17 671.5	0.049	0.141	1 in 7
Case 2 - 0.5 A	88 586	0.246	0.708	1 in 1.4
Case 3 - 0.5 A	169 727	0.471	1.456	1 in 0.73
Case 1 - 1.0 A	9 161	0.0254	0.073	1 in 13.7
Case 2 - 1.0 A	43 005	0.119	0.342	1 in 2.9
Case 3 - 1.0 A	84 474.2	0.237	0.683	1 in 1.47
Case 1 - 4.0 A	2 290	0.00636	0.018	1 in 54
Case 2 - 4.0 A	10 207	0.028	0.081	1 in 12.4
Case 3 - 4.0 A	22 167	0.0616	0.177	1 in 5.6

the MLL ratio in proportion to the change. It should be noted that, as the effects of the step potential are decreased, the contribution associated with the side flashes to the total danger will increase.

Until greater certainty can be made regarding the lethal currents and paths that will be taken through the body, it is advisable to look at a number of scenarios for a given space, thus providing a relationship of the minimum and maximum expected dangers. The MLL method removes the necessity to consider the probabilities associated with consequential loss as per IEC 62305-2. This method also determines the limits that a potential strike may result in a fatality, however, it is not limited to assuming a death will occur and therefore provides insights into the potential for an injury as well.

6.4 Action Volume Ratio - AVR

The MLL method has its primary application to outdoor environments, where large open spaces can now be assessed and a description of the dangers posed by a lightning strike can be presented. This can be seen strictly as a two dimensional analysis, where it would often be assumed that the surrounding objects are significantly larger than the living beings in the area. It can also be considered that in most cases, the living beings are located on the ground.

The AVR method expands on the MLL method in terms of the application of injury mechanisms, the space under analysis, and the limits of the lightning return stroke current. The MLL is determined at the median of the probability distribution function for a lightning negative return stroke current. In the case of the AVR, the assessment has no restrictions on what peak lightning current can be used. For comparative analysis of a space, the AVR could be calculated using the 5^{th} percentile or 95^{th} percentile of the probability distribution function for negative lightning. The Action Volume Ratio (AVR) is defined by:

$$\Omega \qquad : \qquad AVR \equiv \frac{\bigcup_{i=1}^{n} \bigcup_{j=1}^{m} A_{mech\,j} \Big|^{attachment\,@\,i}}{A_{\Omega}} \tag{6.4}$$

where

$A_{mech\,j}$ = Total area/volume defined per injury mechanism per inanimate object in a volume

A_{Ω} = Total area/volume being assessed

For the space under investigation, each injury mechanism is considered in turn - this is denoted in *Equation 6.4* as j. This is performed for every object, i, in the space. The objects are any inanimate items within the space. Within a closed volume such as a structure, this could be internal wiring, water pipes, appliances, or metal frames, such as windows. The volume that may become dangerous is the union of all the dangerous volumes as determined for each injury mechanism. Accepted electrical engineering equations are used to calculate the distances over which a flashover or a step potential may develop. These would be based around the peak return stroke current as well as the resistance, impedance or capacitance of the conductive paths within the volume being assessed. The process also removes the uncertainties associated with many risk models where weighting factors, such as the risk of fire, are included which may not truly represent the scenario correctly. *Figure 6.2* shows an illustration of the dangerous volume to the total volume for a space under analysis. In the figure, the red areas represent those volumes where an injury mechanism may occur - therefore these volumes are considered to be dangerous. The ratio, together with the ground flash density, can be used to determine appropriate methods to reduce the dangerous volumes, thereby reducing the AVR.

As new studies are performed, additional injury mechanisms may be defined which can be easily integrated into this method. The application of the AVR method will now be discussed, looking at two scenarios. The first is for an informal or temporary structure, and the second is for a sports stadium.

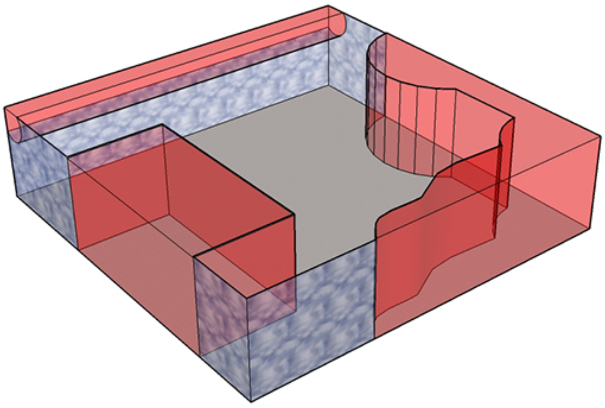

Figure 6.2: Cut-out model representing the concept of the AVR method for a structure. Red areas indicate the union of the dangerous volumes within the structure.

6.4.1 Analysis of an informal structure using the AVR method

In South Africa, there are a number of people who live in informal structures, typically made up of any found material that can be used in the construction process. A number of these structures consist of corrugated iron panels which are then secured to some form of frame. Newspaper or similar materials are used to cover the walls and fill gaps to provide a crude form of insulation from the elements. These structures are found in both urban and rural areas. Typically they will have a basic floor, but this could be anything from a structure built directly on the ground to a laid concrete base. In many cases, the structure is constructed using wooden frames, and then the corrugated iron sheets are nailed or screwed onto the frame. The government had a roll-out scheme to provide electricity to every dwelling in South Africa, thus providing power, but also increasing the occupants' risk of exposure to adverse events from lightning (Dickson *et al.* (2006*b*,*a*)). There is usually a single electrical supply and, in many cases, an external antenna for the terrestrial television signal. The appliances are limited, but would conventionally include of a single or double element counter-top stove, a kettle, some lights, and either a radio, a television, or both.

The structures have either a single room, divided by fabric, or may consist of a few rooms with some form of dividing wall. An illustration of a typical informal structure used as a dwelling in South Africa is shown in *Figure 6.3*. For the application of the AVR method, a basic informal structure of $4\,\mathrm{m}^2$ with a ceiling height of $2\,\mathrm{m}$, is con-

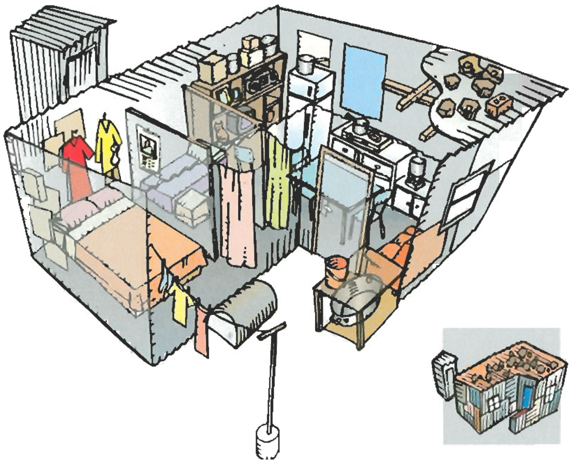

Figure 6.3: Illustration of an informal structure found in South Africa (Eskom (1997))

sidered. The structure has an electrical supply which is terminated at a self-contained distribution board, designed for informal structures. From this, two plug sockets provide power to a two plate stove and a television. The television has an external aerial attached. The ground is concrete and covered by strips of carpet. The walls of the structure are made of corrugated iron sheets.

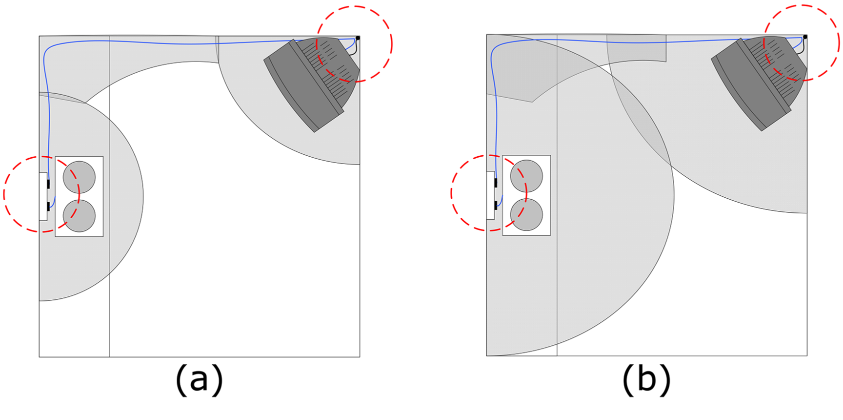

Figure 6.4: An informal structure with dangerous areas defined for two injury mechanisms: (a) is for touch potentials, (b) is for side flash.

In performing an assessment of the structure, it is assumed that injuries associated with a direct strike, as well as from an upward leader, are not possible. The flooring, being covered in carpet and made of concrete, is assumed to limit the development of a step potential. Consideration is only given to the injury mechanisms of touch potentials and side flashes. In *Figure 6.4 (a)* the grey areas define the plan view of the dangerous areas with regard to touch potentials. The red dashed circles represent the point of entry of cables into the structure. In the areas surrounding the television and the stove, the vertical areas above these objects could also expose a living being to a touch potential. The same method is applied in *(b)*, which represents possible side flashes. This would be assumed to occur if the di/dt component of the lightning is sufficiently large, resulting in the development of very high potentials, which, based on the integrity of the electrical installation, may result in breakdown of the insulation and cause a flashover. By comparison in most conventional residential structures, better insulation of conductors and appliances would inherently limit these dangers, therefore, resulting in a smaller AVR.

6.4.2 Analysis of an open air stadium using the AVR method

A second example of the application of the AVR method is in the analysis of an open air stadium. *Figure 6.5* shows the stadium with a sports field. The stadium has open air grand stands and six light towers located around the pitch. The footprints of the light towers are indicated by black circles. As the grand stands are open, all spectators would be exposed to the possibility of direct strikes, as well as the formation of upward leaders, resulting in AVRs of 1. However, the application of the rolling sphere method over the stadium, would indicate that the attachment would probably be to one of the light towers. Therefore, the AVR analysis would be concentrated on the development of touch and step potentials, as well as side flashes. In *Figure 6.5* the pitch is outlined in black. The yellow lines indicate the dangerous areas associated with a step potential and side flash. Both of these two areas already include the dangerous areas for a touch potential. The step potentials are marked with the solid line and the side flash with dashed lines.

Additional parameters would be essential in an accurate assessment of an open space such as a stadium. For instance, the earth resistivity as well as the grounding of the light towers, would be critical components in understanding the true dangers within the area. furthermore the height of the light towers would also affect the application of the rolling sphere method over the structure, and therefore the possible attachment points.

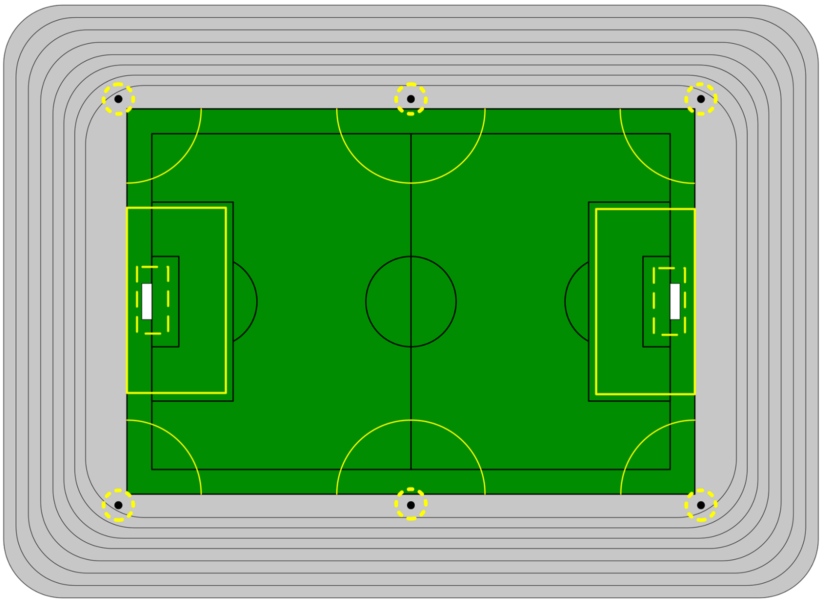

Figure 6.5: A sports stadium, depicting a soccer pitch, with surrounding grand stands. The yellow lines indicate the limit of dangerous step potentials (solid) and side flashes (dashed).

6.5 Summary

The parameters required in developing a method to determine the risk of lightning is complex. In addition, the probabilities associated with a single event are highly dependent on the scenario and the lightning characteristics. In many cases, these probabilities can be qualified in their own respects, but how they relate to each other is problematic. The outcome of a lightning interaction with a living being also has a high degree of uncertainty. The current path is critical, as well as the amount of energy a living being is exposed to. The consideration of the type of living being in the space being assessed, with respect to their physiology, will have a marked effect on the outcome of the lightning interaction.

The AVR method, which was developed out of the MLL method, has been proposed as an alternative for the analysis of any volume with respect to the dangers of a lightning strike. The AVR method removes the weightings associated with probability and losses used in conventional risk assessment processes (IEC 62305-2), and conceptualises the danger associated with lightning by identifying the dangerous volumes for each type of lightning injury mechanism. By forming a union of all these volumes, the ratio of the dangerous volume to the total volume can be calculated. The AVR can also be determined for any percentile of the probability distribution function for negative return strokes. The AVR method has particular application to the assessment of open spaces. A number of examples have been used to show how the AVR method can be applied.

In the next chapter, the application of the AVR method is used to assess the enclosure of critically endangered antelope in the National Zoological Gardens, Pretoria, South Africa.

Chapter 7

Case study: Critically endangered Kenyan Mountain Bongos (*Tragelaphus euryverus isaaci*)

In this chapter, an animal enclosure in the National Zoological Gardens (NZG), in Pretoria, South Africa, is assessed using the Action Volume Ratio (AVR). The assessment is considered only for the median peak current value of a negative lightning return stroke, as per the probability distribution function, as defined by the IEC. By the definition in *Chapter 6, Page 78*, this case study will use the Median Lethal Limit (MLL) for the analysis. This is because the space being assessed is effectively a two dimensional system, where the space is limited to that area of the enclosure where the animals are found. The significance of this assessment is the fact that it highlights the dangerous areas in the enclosure. The interest in this case is that the animals were Kenyan Mountain Bongos (*Tragelaphus euryverus isaaci*), which are a critically endangered species.

7.1 Topography of the enclosure and surrounding area.

The National Zoological Gardens (NZG) are located in Pretoria, in the Gauteng province of South Africa. The lightning ground flash density for the area, according to the Lightning Detection Network (LDN) data, from the South African Weather Service, is between 10 and 15 flashes/km^2/year. The NZG is located to the north of the city centre, and its northern border goes up to the crest of a ridge. An aerial view of the

Figure 7.1: High aerial view of the National Zoological Gardens in Pretoria

NZG is shown in *Figure 7.1*. The yellow line denotes the perimeter of the NZG. The white box provides more details regarding the enclosure, and is shown in *Figure 7.2*. In *Figure 7.2* the enclosure under investigation is outlined in white. The tree that was struck is within the white circle. The tallest nearby point is the roof of the upper terminal of the cable car system, marked with a yellow box. The top of the ridge is marked by a yellow line. On the top of the ridge is an aviary, which is made of netting, which rests on two 3.5 m aluminium poles. The enclosure is approximately 72 m long by 86 m wide. The distance, from the tree that was struck, to the top of the ridge, is approximately 123 m. The distance from the tree to the cable car station is 194 m.

Figure 7.3 is taken from within the enclosure looking North. The circles indicate the tree that was struck, and the top of the ridge, where one of the poles of the aviary can be seen.

There is a buried water pipe, located in the northern part of the enclosure, with a vertically mounted tap at the enclosure perimeter. There are no other known services within the enclosure. Near the enclosure, there is a shelter to provide shade, or protection for people during a storm. The shelter has a thatch roof and is protected by a lightning mast. By applying the principles of the angle of protection and the rolling sphere method, the lightning mast affords no protection to the enclosure. The animals have a brick and concrete shelter on the eastern boundary of the enclosure.

Figure 7.2: Aerial view of the enclosure, the crest of the hill and the upper terminal building of the cable car system.

Figure 7.3: View to the North, taken from inside the Mountain Bongo enclosure, showing the nearby ridge.

7.1.1 Storm data

The Weather Service's LDN has a 95% detection efficiency in the area of the NZG, with an accuracy of under 500 m (Grant *et al.* (2012)). The stroke detection efficiency of the combined time of arrival and magnetic direction finding networks, is in the region of 60%.

From the analysis of the data, there are a number of strokes that could be responsible for the animals' deaths, however, there is also a possibility that the actual stroke was not detected by the LDN network. Grant *et al.* (2012) analysed the LDN data for the period that the incident was believed to occur. A collection of strokes were identified as the possible event. They occurred around 22:55 on the evening of the 11^{th} of January 2012. Within this, a single event that occurred at 22:55:23 is the most probable strike, which had a peak current of -23 kA (Grant *et al.* (2012)).

7.1.2 Soil resistivity data

Soil resistivity measurements were performed around the tree that was struck. Four measurement were taken at spacings of two metres from the tree, with the earth rods spaced at 0.5, 1, 2 and 3 m distance. The measurement data is shown in *Table 7.1.* In addition, measurements were taken radially outward from the tree to the nearby fence and water service. The average earth resistivity for the enclosure was determined to be $101\,\Omega m$.

Table 7.1: Earth resistivity data, measured within the enclosure, at the base of the tree where the Mountain Bongos were killed.

Delta (m)	A (Ω)	B (Ω)	C (Ω)	D (Ω)
0.5	19.35	27.6	29.3	27.9
1	13.69	18.68	16.76	17.65
2	8.36	10.32	8.45	8.96
3	6.16	5.91	5.51	4.48

7.1.3 Site investigation

The tree, under which the animals were found, had scorch marks down the trunk. Both animals were found lying with their heads facing towards the trunk of the tree. There were no burn marks on the animals, as well as no entry or exit wounds. The orientation of the animals, places the medial line of their bodies radially outward from the tree, with no indication of a direct strike, or side flash. This would suggest that the mechanism of death was a step potential. As an additional note, the resident vet informed the investigation team that, originally, there had been a single enclosure, instead of the two enclosures now in operation. During this time, approximately 10 years ago, a Sable Antelope was directly struck by lightning, which resulted in the animal's death.

7.2 IEC 62305-2 risk analysis of the enclosure

The IEC 62305-2 risk management document is not designed for assessments in outdoor and open areas. However, it can provide an indication for the purpose of comparisons, by performing basic analyses. This section will present two methods for assessing the risk to the tree and enclosure.

7.2.1 Risk assessment for the tree

In the first assessment, the tree is considered to be a single entity, or structure, that will be evaluated for the possibility of a fatality. The two uncertainties are the exact lightning ground flash density, and the height of the tree. The results of the risk analysis are shown in *Figure 7.4*. The risk, even in the worst case scenario, is well below the tolerable risk for the loss of life of 1×10^{-5}. This would indicate a minimal risk to the tree being struck and a fatality occurring.

7.3 Risk assessment for the collection of trees

In the second analysis, the trees in the northern section of the enclosure are grouped together, and the risk assessment performed accordingly. The results of this analysis are shown in *Figure 7.5*. In this analysis, it is considered that all risk assessments are

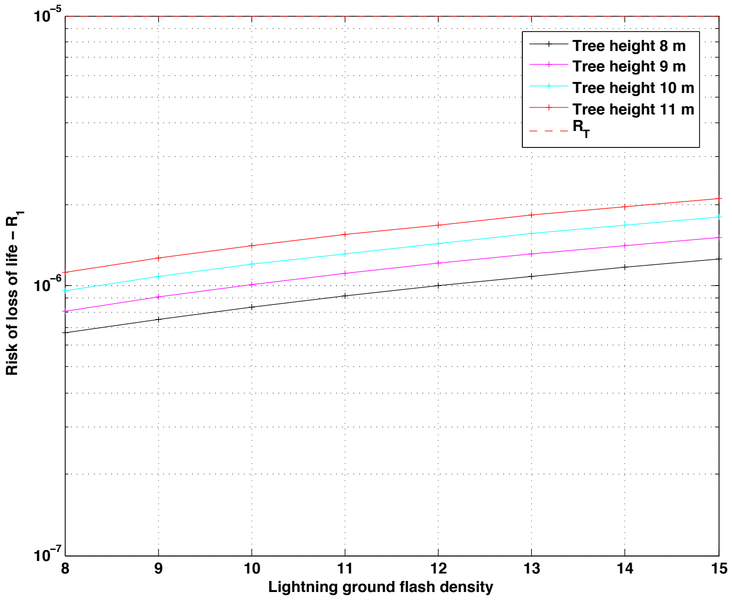

Figure 7.4: The IEC 62305-2 risk analysis for the tree being struck, and resultant loss of life.

greater than the tolerable risk for the loss of life, and that some form of protection measures should be considered. If the resultant values are compared to the tolerable risk for the loss of cultural heritage, 3×10^{-3}, no protection measures would be required.

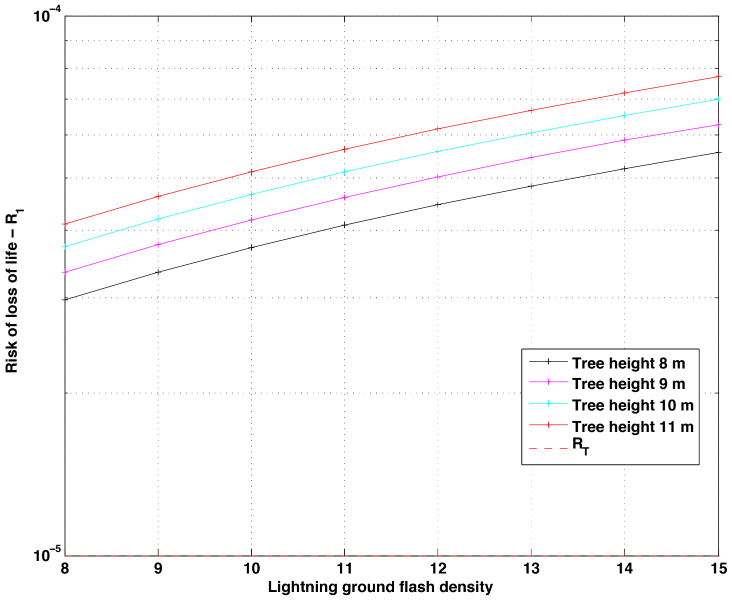

Figure 7.5: IEC 62305-2 risk assessment to collective grouping of trees in the enclosure.

7.4 Application of the Median Lethal Limit (MLL) method

The application of the *Equation 4.4*, is used to assess the step potential from the point of strike, using an earth resistivity of 101 Ωm as determined from the site evaluation. A step length of 1 m is selected, though the length between the front and hind legs of the animals may be as much as 1.5 m. *Figure 7.6* shows the results of the possible step potential that can be developed within the enclosure, for lightning with different peak return stroke currents.

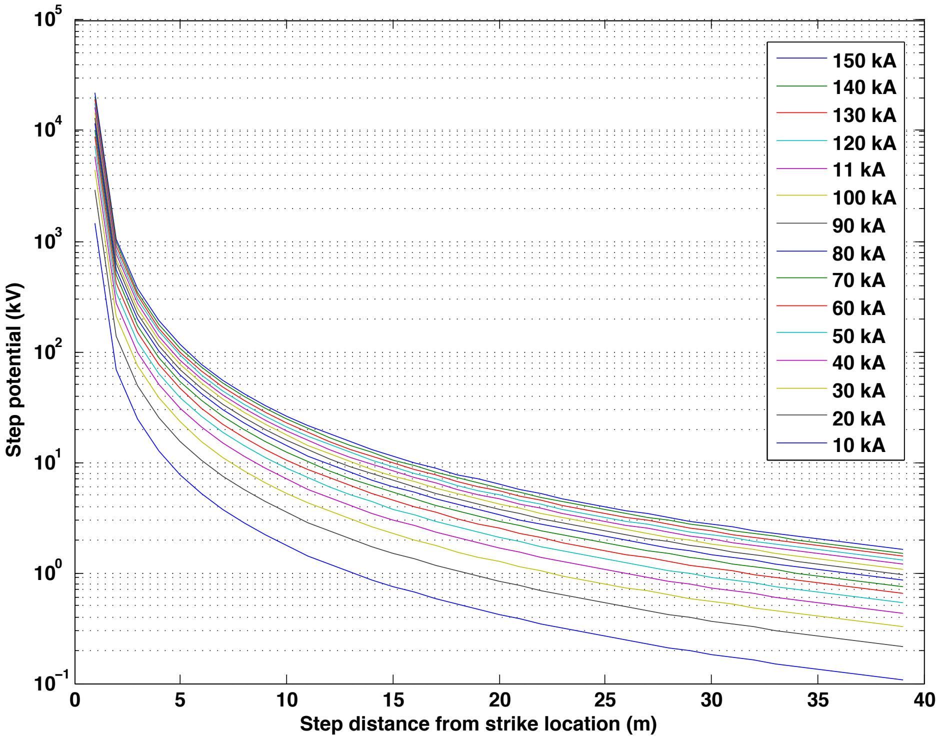

Figure 7.6: The calculated step potentials that can be developed in the enclosure, for different lightning peak return stroke currents. Step length is 1 m and $\rho = 101\,\Omega m$.

The MLL is applied to the enclosure under the following conditions. The impedance of the Mountain Bongo is assumed to be 2000 Ω. This is broken down into 800 Ω for the legs, and 400 Ω for the thorax. The legs are considered as higher impedances than those of a human, as well as having the natural insulators of the hooves, though, in the event that the soil was damp, they may provide very little resistance to any ground currents. These estimates are probably on the conservative side, but this only increases the final risk. A current parameter that may result in serious injury or death for quadrupeds is

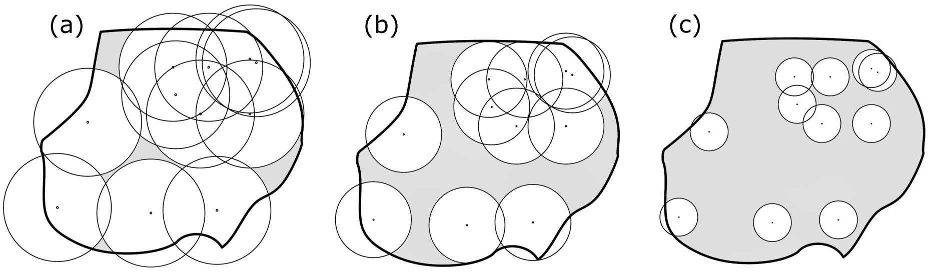

Figure 7.7: The visual presentation of the MLL for different lethal currents within the enclosure. The currents developed, as per the figure are: (a) 0.5 A; (b) 1 A; (c) 4 A.

considered, in most cases, to be lower than those of bipeds. The current path developed as a result of a step potential, will generally pass through the thorax, and therefore, pass through the heart. For this analysis three currents are investigated, which are 4 A, 1 A and 0.5 A. All these currents have the potential to cause serious injury or death. From the graph in *Figure 7.6*, the step potentials that would result in these currents, occur at radii of 6.3 m, 12.6 m and 17.9 m from the point of strike.

The ratios that are determined from the figures (a - c) of *Figure 7.7*, are presented in *Table 7.2*.

Table 7.2: MLL results for the different areas calculated from *Figure 7.7*.

		Incidence		**Frequency (years)**	
Description	**Ratio - $\frac{A_l}{A_T}$ (%)**	**Ng = 10**	**Ng = 15**	**Ng = 10**	**Ng = 15**
Case 1 - 0.5 A	92.8	0.0466	0.0699	1 in 21	1 in 14
Case 2 - 1 A	66.5	0.0334	0.05	1 in 30	1 in 20
Case 3 - 4 A	25.8	0.012	0.019	1 in 83	1 in 53

7.5 Discussion

The enclosure has a relatively low soil resistivity, which limits the distance that a lethal step potential can be developed. However, as shown in the first two cases, the MLL ratio is considerably high. This places all living beings in the enclosure at considerable risk from a lightning event. If the lethal current is significantly smaller than this, the tendency would be that the entire area would be considered as dangerous. If consideration is given to case 1, with a lethal current of 0.5 A, the ratio is at 92.8 %, and results in a frequency of 15 years, for a ground flash density of 15 flashes/km^2/year. Considering that another animal was killed in the enclosure 10 years ago, this may indicate that ground flash density for the area is at the higher end of the scale. Some form of protection measures should be put in place. This may take the form of a lightning protection system, with emphasis on the air termination system. Alternatively, an early warning system, which results in the animals being placed in a place of safety during a thunderstorm, could be used.

7.6 Summary

This chapter has demonstrated the application of the AVR method, using the MML process, in assessing an outdoor space. The lethal current limit is the only factor which is uncertain. By assessing the enclosure for a number of different currents, a comparative study can be made, and appropriate actions can be taken to reduce the ratio. This could be done by providing an adequate air termination system, or by reducing the earth resistivity values in the enclosure. If the value of the animals' body impedance is smaller, then the ratio will decrease, placing the animals at a greater risk.

In the next chapter, the MLL method is applied to an enclosure on a farm where a herd of cattle were killed by a lightning strike.

Chapter 8

Case study: 22 cattle killed by lightning

In this chapter, the AVR method is applied to a cattle enclosure, located on a farm in the Mpumalanga province, South Africa. A lightning strike resulted in the deaths of 22 cattle. A transmission line crosses the enclosure, which provides a certain amount of protection, and the case study provides an opportunity to present how different objects in the environment are considered when calculating the AVR. The concepts of the collection area and rolling sphere model are used in the analysis.

The event occurred on the night of the 15 November, 2012. The farmer recalls that a large electrical storm had occurred in the night. The next morning, 22 cattle were found dead, grouped together under a collection of trees located in the enclosure. A vet, resident in the area, visited the scene on the morning after the event. She confirmed that the animals had been killed by lightning.

8.1 Topography of the farm and enclosure

The farm is located approximately 164 km east of Johannesburg, in the Mpumalanga province in South Africa. The average lightning ground flash density for the area is between 10 and 15 flashes/km^2/year. The farm is located near a national highway, in the geographical region where the majority of the coal fired power stations of South Africa are located. The farm is located at the crest of a hill, with a gradient across the farm of approximately 1:12.5, from west to east. The gradient of the hill leading up to the farm is approximately 1:18. A 275 kV transmission line runs diagonally across the enclosure, the earth wire conductors are located at a height of 25 m above the ground. An aerial view of the enclosure is shown in *Figure 8.1.* The enclosure is marked with a black line. Each tree of the group where the cattle were found, is marked with a green dot. The tree that was struck, is marked with a blue and green circle. The transmission line is indicated by an orange line. The enclosure is approximately 250 m long, and 158 m and 118 m wide at the western and eastern ends respectively. There are two small dams in the enclosure. The small one located near the trees, had a small amount of water in it. All the trees located in the enclosure are black wattles, which have a broad based shallow root structure.

Figure 8.1: Aerial view of the enclosure with the trees, dams, and transmission line marked.

8.1.1 Soil resistivity measurements

As already mentioned, the smaller dam in the enclosure is located just above the trees where the cattle were located at the time of the event. The soil is well worked and mixed with cattle dung. The area where the cattle were killed is shown in *Figure 8.2.* The soil type would be best described as loamy, and there is a significant amount of loose earth and vegetation for the first ten centimetres. Soil resistivity measurements were conducted using the line traverse method. Four lines were measured in a north-south direction and, similarly, in an east-west direction. The graph in *Figure 8.3* shows the average soil resistivity for each direction of the line traverses. The soil resistivity is relatively uniform at a depth greater than 3 metres. The earth resistivity at this depth is approximately 300 Ωm. The soil resistivity at the surface is approximately 200 Ωm.

Figure 8.2: The location where the cattle were killed, with the tree on the left hand side of the photo being the tree believed to have been struck.

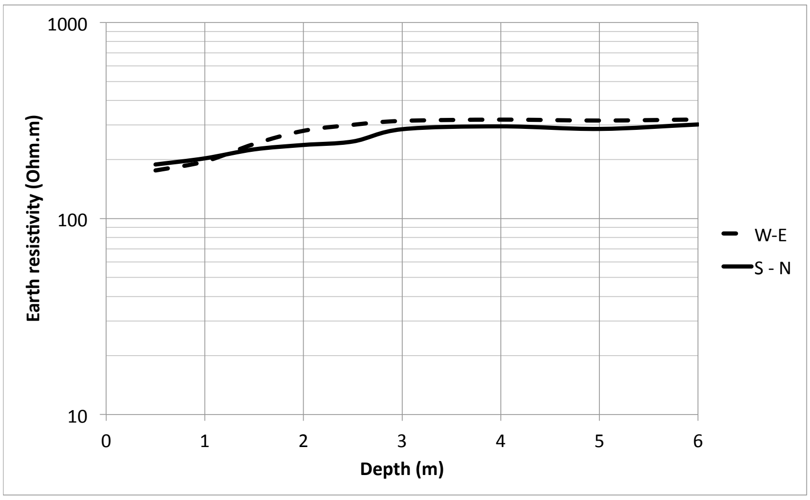

Figure 8.3: Graph showing the soil resistivity for the area where the cattle were killed. Each line represents the average recorded soil resistivity, for each of the traverse directions.

8.1.2 Site inspection the morning after the strike

Figure 8.4: The herd of cattle killed by lightning. The tree in the centre of the image is believed to have been struck.

A vet was on site the morning after the incident and took photographs of the cattle before they were moved. *Figure 8.4* shows the entire group, with a number of cows lying next to the tree that was struck, the rest are spread out radially behind the tree. *Figure 8.5* shows ten of the cows that were located between 12 and 15 metres from the trunk of the tree. From the site investigation on the morning after the incident, it was determined that a number of the cows were probably standing when the strike occurred. As certain of the cows were entangled with each other as well as some of the vegetation, there were no visible signs of distress or seizures of the animals. On some of the cows examined, burn marks were identified, and these are shown in the photographs in *Figure 8.6*. Cattle with lighter hides, clearly showed burn marks, however, in the case of cattle with darker hides, no visible indications of burns were seen. On one of the cows, burn marks were seen on both of the hind legs.

Figure 8.7 shows the outline of the enclosure, as well the collection of trees and transmission line. The dashed black box around the transmission line indicates its collection area, as per the IEC 62305-2. If the trees are grouped as a single object, their effective collection area is defined by the grey dashed line. It is assumed, for this case, that all trees are of equal height. The tree believed to have been struck is on the limit of the collection area of the transmission line. In *Figure 8.8* the rolling sphere method is performed between the transmission line and the tree. The dotted line indicates the IEC recommended calculation for the strike distance for a 20 kA peak return current. The small sphere is based on a Lightning Protection Level (LPL) of 1, and the large sphere is based on a LPL of 4. In the case of larger peak return current values, it would be assumed that either the trees or the transmission line could be the point of attachment. However, this would not apply for the entire enclosure, as can be seen in *Figure 8.7*.

Figure 8.5: One of the groups of cattle, located to the north west of the tree.

Figure 8.6: Burn marks on the hide of two of the cattle.

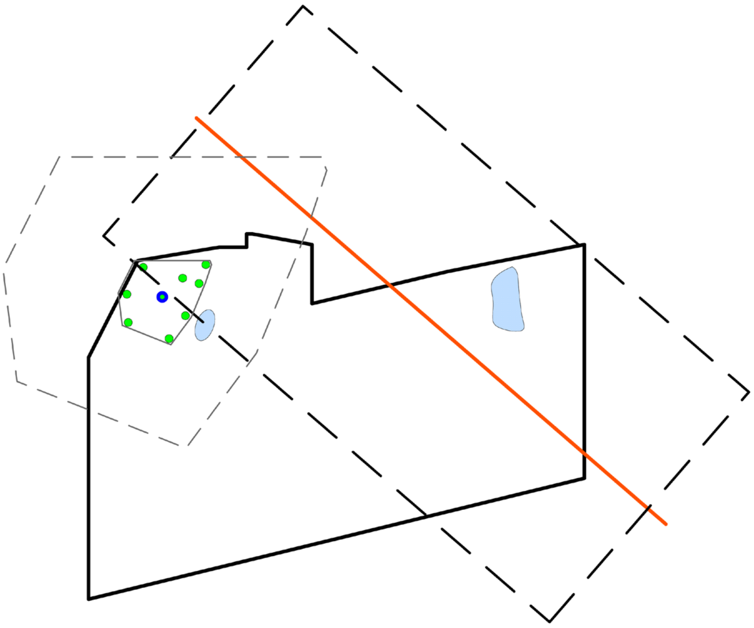

Figure 8.7: Outline drawing of the enclosure, transmission line and trees, including the collection areas for the transmission line and collective of trees, as per the IEC 62305-2 risk management standard.

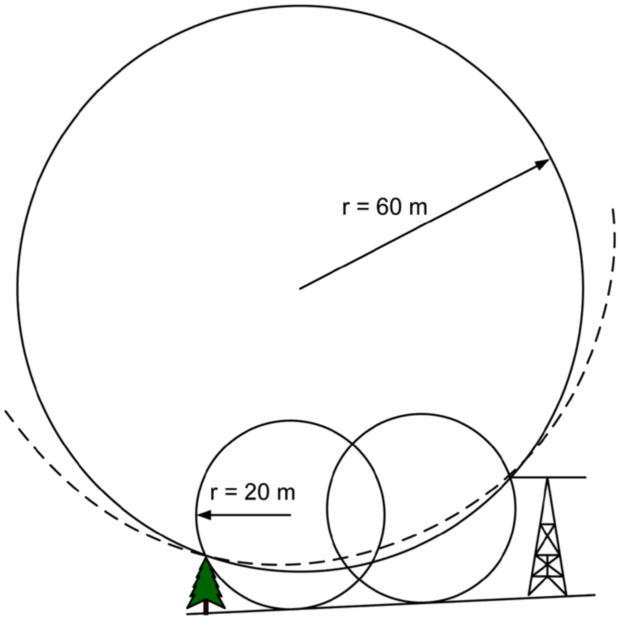

Figure 8.8: Relationship of different rolling sphere radii and the striking distance (dashed line), as defined in IEC 62305-1.

8.2 Analysis of the probable lightning path

Figure 8.2 shows the collection of trees at the bottom of the enclosure, the tree with the blue circle is the best assumption for the location of the strike. There was, however, no indication of a lightning channel through the bark of any of the trees in the area. On one of the branches of the tree, considered to the point of attachment, some of the bark had been removed, or opened, as shown in *Figure 8.9*.

Figure 8.9: A branch where the bark has been disturbed, which may have been as a result of the lightning strike.

With the evidence, and the limited number of burn marks on the cows, it is hypothesized that the tree was struck, but that it was already raining, and the path of the strike travelled through the branches of the tree, flashing over to one or more of the cows standing underneath the branches. This provided a path to ground. With the environment already wet from the rain, and with the loose vegetable matter on the surface of the ground, part of the current entered the earth, but a component resulted in a surface arc. Between these two mechanisms, various animals succumbed to high step potentials, resulting in cardiopulmonary or cardiorespiratory arrest. No autopsies were performed, so the cause of death is unknown. There were no signs on the ground of any distress and no indication of strained or stressed breathing.

8.3 IEC 62305-2 risk analysis of the enclosure

The IEC 62305-2 risk analysis method is applied to the enclosure, by considering the collection of trees as a structure. The assessment is performed considering only risk type 1, loss of life (R_1). The collection area, as defined in *Equation 3.4*, the ground flash density (N_g) and IEC 62305-2 proposed loss factors, are used in the analysis. For the sake of a simpler risk analysis, the transmission line collection area is excluded from the analysis. By leaving out the transmission line collection area, the risk will be higher indicating, a worse case scenario. The transmission line does, however, affect the location factor value. The analysis is performed for a number of different tree heights, ranging between 8 m and 16 m. The analysis is also performed using lightning ground flash densities of between 10 and 15 flashes/km^2/year. The results of the analysis are shown in *Figure 8.10.* The tolerable risk for the loss of life is 1×10^{-5}. In all cases, the risk of loss of life is below the tolerable risk and, therefore, the necessity for protection would not be required.

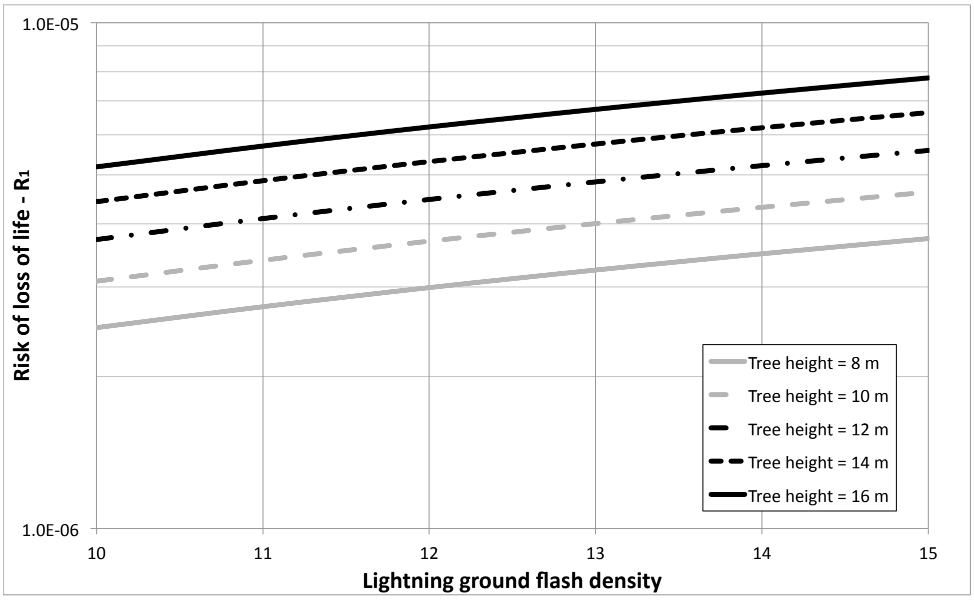

Figure 8.10: IEC 62305-2 risk assessment for the loss of life (R_1), where the collective of trees represents the structure.

Selected Values of the IEC 62305-2 risk assessment are shown in *Table 8.1.* Only in the case of a large tree height, and a high ground flash density, is the risk comparable to the tolerable risk.

Table 8.1: Summary of IEC 62305-2 risk analysis for the loss of life, for the cattle enclosure.

Parameter values	**Risk R_1 (yr^{-1})**	**Risk in man years**
h = 8, Ng = 10	2.49×10^{-6}	1 in 401 606 years
h = 8, Ng = 15	3.74×10^{-6}	1 in 267 379 years
h = 18, Ng = 10	6.00×10^{-6}	1 in 166 666 years
h = 18, Ng = 15	9.00×10^{-6}	1 in 111 111 years

8.4 Application of the Median Lethal Limit

Using *Equation 4.4*, the step potential for a lightning strike with a peak return stroke of 20 kA, can be calculated. *Figure 8.11* is derived from *Equation 4.4*, with an I_p of 20 kA. The calculations used the lower and upper limits of the measured earth resistivity (ρ = 180, 320 Ωm), and step lengths of 1 and 2 m. The distance between the tree and the perimeter fence is about 22 m, so the calculations were performed up to 25 m.

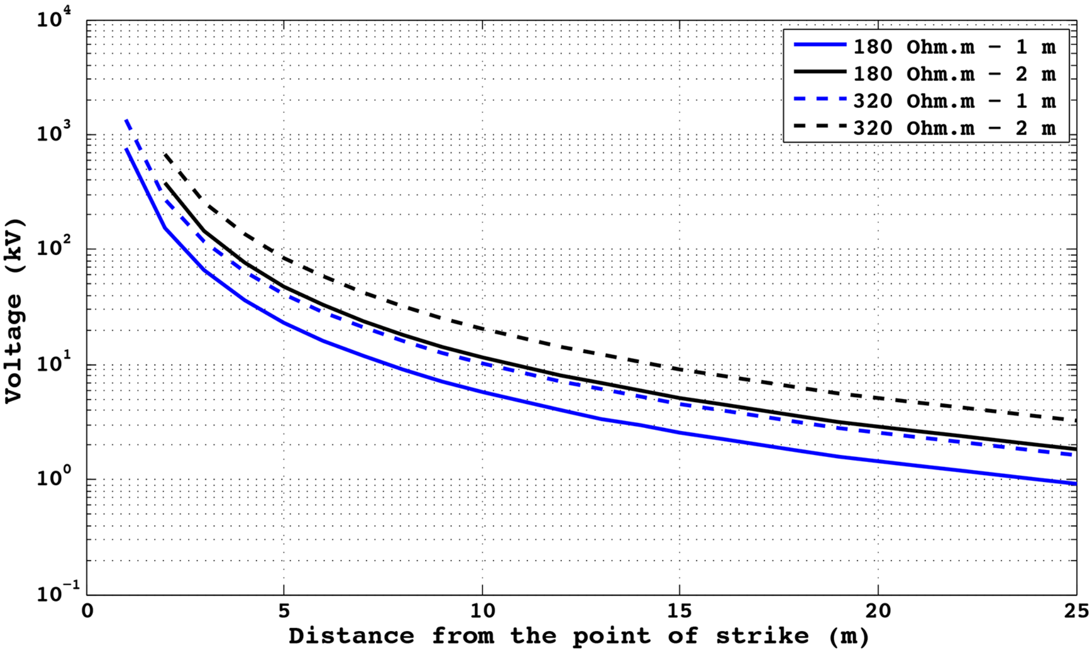

Figure 8.11: The calculated ground potential rise for a peak return stroke current of 20 kA. Two step lengths and two soil resistivities are shown.

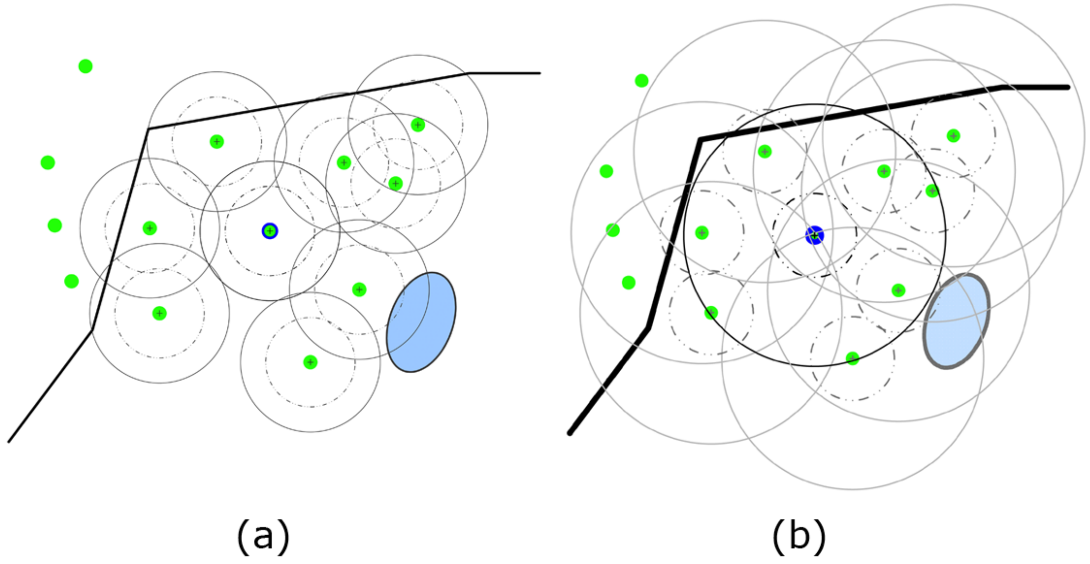

Figure 8.12: Circles indicating the Median Lethal Limit for (a) a step potential of 4 A can be developed for a step length of 1 m. The solid and dashed lines represent the maximum (320 Ωm), and minimum (180 Ωm) measured earth resistivities, respectively. (b) a body current of 0.5 A, with a step length of 1 m. The earth resistivity used is 180 Ωm.

Figure 8.12 (a) shows the lethal limit areas, for the development of a 4 A body current, where the earth resistivity of 320 Ωm is indicated by the circles with a solid line, and 180 Ωm, by the dashed lines. *Figure 8.12 (b)* shows the worst case scenario where the soil resistivity is considered to be 320 Ωm, and the lethal body current is 0.5 A. The area is defined by circles with a solid line.

The results of the analysis using the Median Lethal Limits are shown in *Table 8.2.* The results, with a description of *transmission line*, incorporate the collection area of the transmission line as defined by the IEC 62305-2 standards, in the analysis. This has the impact of doubling the expected frequency of events. By applying the rolling sphere model to objects, the result is a truer reflection of the expected number of events that could occur to the trees in the enclosure.

Table 8.2: The results of the application of the MLL method to the cattle enclosure.

Description	**Ratio - $\frac{A_l}{A_T}$ (%)**	**Incidence** **Ng = 10**	 **Ng = 15**	**Frequency (years)** **Ng = 10**	 **Ng = 15**
12.5 m	9.11	0.0295	0.0445	1 in 34	1 in 23
12.5 m Transmission line	11.29	0.01625	0.0244	1 in 62	1 in 41
25 m	15.12	0.049	0.0734	1 in 20	1 in 14
25 m Transmission line	19.71	0.0284	0.0426	1 in 35	1 in 24

8.5 Discussion

The earth wires of the transmission line that crosses the enclosure provide a certain amount of protection from lightning. In performing the analysis, the inclusion of the transmission line increases the ratio, because the effective area of the enclosure changes. The frequency indicates that the inclusion of the transmission line in the results almost doubles the time between incidents. The analysis of the enclosure using the rolling sphere method indicates that the transmission line does not provide as much protection as would be gained by using the collection area method proposed by IEC 62305-2. The results of the MLL analysis indicate that, if a lethal current of 0.5 A is used, the entire area where the trees are present would be dangerous to quadrupeds. The frequency of 1 in 14 years is a relatively high frequency, and would indicate that some form of protection should be considered. Alternatively, a structure or smaller holding pen, with adequate protection measures in place, would significantly reduce the chances of losses in the future.

8.6 Summary

This chapter has presented a case study where 22 cattle were killed by lightning. Though the MLL ratio is relatively small, the frequency is quite high, because of the total area. Therefore some form of protection measures would be recommended. The presence of the transmission line needs to be carefully handled, as the results of an analysis could be skewed if a conventional collection area methodology is applied. The rolling sphere method, in combination with the MML method, provides a comprehensive analysis tool for the assessment of lightning dangers in open spaces.

Both case studies presented relate to animals, rather than human beings. There are two primary reasons for this. Firstly, the application of the AVR can be applied to any space, used by any living being, but careful consideration needs to be given to the lightning injury mechanism and, therefore, the interaction it may have with a certain type of living being. Secondly, the case studies have occurred recently and extensive investigations were performed. Recent lightning incidents involving (human) living beings have certain ethical and legal issues associated with them, thus delaying the analysis process.

In the next chapter, the conclusion of this thesis is presented.

Chapter 9

Conclusion

The Action Volume Ratio (AVR) is a new method that describes the dangers associated with a lightning strike within any volume. This method uses accepted engineering principles to determine the dangers associated with different lightning injury mechanisms within the volume being assessed. The union of the dangerous areas is summed and divided by the total volume to determine the AVR. This method can be used in both a technical assessment, as well as an aid in educating lay people about the dangers of lightning within a given volume.

This work provides the following contributions:

- The Action Volume Ratio method describes the dangers of lightning in any volume. This includes open spaces, within structures, and the areas of transition between structures and open spaces.
- The AVR method departs from traditional risk analysis methods, and thus does not rely on probability or loss factors.
- The AVR can be considered for both injuries and fatalities, providing a more comprehensive analysis of a given volume.
- The method can incorporate additional lightning injury mechanisms as they are discovered.
- Presentation of the results is accessible to engineers and lay people alike.

Location and incidence

The number of lightning fatalities has been decreasing steadily over the last century. This can be attributed to urbanisation, education and an increased understanding of the lightning phenomenon. An estimation of the world average mortality rate in lightning related incidents is 3 deaths per million per year. This varies, from the United States which has a value below 1 (Holle (2012*a*)), to Swaziland where the estimation is approximately 15 (Dlamini (2009)). There are many countries where information is not available or is severely under-reported. The majority of lightning related injuries and fatalities occur in countries with high ground flash densities and large rural populations. This includes much of Africa, Asia and South America. These areas also report higher incidences of indoor lightning injuries and fatalities, however, this is often because of the lack of regulation for informal structures which provide the occupants with little inherent protection from lightning.

Outdoor activities account for the majority of lightning injuries and fatalities. The most obvious argument is that when thunderstorms approach, a place of safety should be sought. In the case of humans, several factors come into play. Cultural beliefs, partial knowledge, necessity, or a belief that the probability of an adverse event is so small, often results in the decision that no action needs be taken to reduce the risk. Many humans caught in a thunderstorm seek shelter from the rain by taking refuge under a tree, thus increasing the likelihood of an adverse event. A lightning incident generally occurs during some recreational activity, with the exception of construction and agricultural workers. In most cases, there are usually only one or two victims. However, there have been incidents with multiple victims - these are usually associated with team sports, hiking, camping and army activities. Activities which have a high incidence of lightning injuries and fatalities include soccer, baseball, golf, camping, boating, fishing and agriculture. Lightning incident data around the world shows similar characteristics. Men are struck more often than women, most are below the age of 35, and the majority of events occur outdoors.

Animals will be exposed to all lightning injury mechanisms, unless they are herded into a place of safety. In many cases, animals seek shelter under trees, near temporary shelters, or next to fences. This will generally increases their risk of an adverse event.

Living beings and lightning currents

Kitagawa *et al.* (1973) performed many experiments on animals in an attempt to understand the phenomenon of lightning impulses and how they interact with the body. A value of 62.6 J/kg was considered to be the lethal energy limit the body could dissipate. Anything greater than this would result in death. His work also confirmed that if flashover occurs, the chance of survival increases. Dalziel & Lee (1968) performed work on human subjects in an attempt to understand how electricity and the body interact. Kitagawa and Dalziel both determined that a fatality is dependent on the weight of the subject. Dalziel describes an equation that defines the lethal current limit that a living being can withstand. This equation is a relation of the living being's weight and the duration of exposure to the current. The majority of his work was performed at power frequencies of 50/60 Hz. Concerns have been raised concerning the lethal energy level that the body can sustain, with the thought that the level is somewhere between 10 and 50 J (Berger (2007); Szczerbiński (2003)).

A generic model for the impedance of the body is well defined (Cooray *et al.* (2007*a*); Fish & Geddes (2009)). For many studies of the electrical response of the human body, a lumped value of $1\,000\,\Omega m$ is used. Under certain conditions the contact impedance, consisting of a resistor in parallel with a capacitor, is used. The response of tissue within the human body has shown that the nerve and blood vessels are the most conductive paths within the body, and fat and bone are the least conductive. Andrews considers that the electrical response of the body is relatively well understood (Fish & Geddes (2009)). However, further research is still required, but this is limited by ethical and moral issues.

A number of injuries can result from a lightning incident, however, there are two primary causes of death. The first is the interaction of the current with the heart. This can result in ventricular fibrillation or cardiopulmonary arrest, both of which can be fatal as oxygen is not supplied to the rest of the body. The second, is the interaction of a lightning current with the respiratory control centres in the brain. Respiratory arrest can occur, resulting in no oxygen being available for the body. There are a number of other injuries that can result from a lightning incident, and many are resolved within a matter of hours or days. However, there are often long-lasting neurological sequela, which, in some cases are never resolved.

There are considered to be six mechanisms of lightning injury. These are direct, indirect, touch and step, side flash, upward streamer and blunt or barotrauma. The type of mechanism, will have an effect on the outcome of the incident. Often in the event of a direct strike, a flashhover results, thereby limiting the current that will actually flow through the body. However, the current path will typically interact with all critical systems in the body. Cooper (2008) considers that most lightning injuries are as a result of side flash, step potential or upward streamer. These mechanisms present a lower probability of flashover, and therefore larger current through the body. How the current traverses the body is still questionable. There is a belief that a step potential will not result in current passing through the heart. Andrews, however, does state that a small percentage of the current will go through the heart (Cooray *et al.* (2007*a*)). In the case of quadrupeds, there are usually a large number of deaths. This is thought to be because step potentials have a greater effect as any step potential current will pass through the thorax.

How the body of a living being reacts to a lightning impulse is still relatively unknown. Early research has provided a good platform to work from, but there is a limit as to the type of research that can now be performed. Computer simulation models do provide a means of gaining insight into the expected results of an applied impulse to the body. However, there is still a high degree of uncertainty. Consequently, the results may only be accurate in certain circumstances or for certain groups of people, whether it be age or gender specific. Therefore no engineering process can be based on these systems as there are too many variables that are still unknown. A large number of lightning cases have been presented which qualify the fact that each scenario and every interaction is unique. The development of any valid statistical data from these cases is very subjective.

Risk considerations

Lightning detection networks are providing more accurate data of lightning occurrences, magnitudes and locations than in the past. In the context of South Africa, this has shown that the previous lightning ground flash density map under reported events, by anything between 30 and 100 %. This increase could be because of the detection efficiency of the new system, or due to the earth's elevated surface temperatures, resulting in an increased number of recorded lightning events (Price (2008)). The net result is that the lightning risks to living beings are higher.

Lupton (1999) describes risk as an increasingly pervasive concept in our daily lives. Every action or process has some form of risk attached to it. Risk calculations are traditionally based on the realist perspective, which is defined as the probability of losses associated with an adverse event. In many cases, however, risks are judged from a sociocultural perspective, where the background of the person who is considering performing an action, may dictate what they will or will not do. In the same way, many decisions relating to lightning are based on social misconceptions of what events may occur in a particular environment. At the same time, modern society has a tendency to remove responsibility for risk away from the individual. This requires groups, organisations or industries to put in place methods, or mechanisms, to mitigate the risk, thus avoiding blame for an adverse event occurring. International risk standards provide a means of determining risk associated with adverse events. However, there are still concerns over the validity of some of the weighting factors used in the analysis, which then questions the results.

There are currently no methods to determine the risk of lightning in open spaces. It is a valid argument to state that when adverse weather conditions are present, shelter should be sought immediately. However, this is not always possible or desired by living beings. The current international standards determine the risk of the loss of life (R_1) for inside a structure and up to 3 m outside it. As most lightning injuries and fatalities occur outdoors, a means of understanding and presenting the risk associated with lightning in open spaces is required. The development of a method to determine this risk is complex. There are many compounding factors relating to the occurrence of an adverse event. Statistical methods can be used to determine the outcomes, but validating the model is difficult as, in most cases, there is not sufficient data available from forensic investigations to confirm the assumptions.

The Action Volume Ratio (AVR) model

The Action Volume Ratio (AVR) presented in this work, is a method used to determine the ratio of the union of dangerous volumes to the total volume of a space, with respect to lightning. For each lightning injury mechanism, accepted engineering principles can be used to calculate the dangerous area around each object in the space. The union of each dangerous area for each object is then divided by the total volume to provide the AVR. Lightning protection systems can be implemented to reduce the AVR for the space. The AVR can also be combined with the lightning ground flash density in the case of open spaces, to provide an indication of the incidence or frequency of dangerous events for the space.

The AVR avoids weighting factors seen in conventional risk analysis processes. This is because, in many cases, the probabilities are interrelated and scenario specific, and therefore cannot be used for a generic solution. By only considering the electrical parameters, any space can be assessed. The AVR can be expanded to incorporate additional mechanisms as discovered. The AVR can also be calculated for any peak current magnitude as defined by the probability distribution function for lightning negative return strokes. The Median Lethal Limit (MLL) is a subset of the AVR and is aimed primarily at the analysis of open spaces. This method, as per its name, uses the median peak current value for negative lightning strokes. It highlights the dangerous regions and, in conjunction with the lightning ground flash density, can provide relevant information to engineers and lay people alike. The visual representation of the union of the dangerous areas can be easily understood, and can be presented to the general public. The finer details of the analysis, regarding the probability distribution function for negative return stokes, combined with the lethal current level for living beings, provides a powerful analysis tool for an engineering evaluation of a site.

By calculating the AVR, decisions can be made as to the most appropriate lightning protection measures to be implemented, thus reducing the AVR. The AVR does not calculate risk, as it does not consider the probability of an adverse event occurring. The losses are also not considered, as in the case of the lightning risk standards, where the consideration is only for the loss of life. The AVR defines the dangerous areas, but this could be in relation to any injury or fatality.

Two case studies were presented which show both the application of the AVR method, as well as indicating the requirement for protection as, in both cases, the animals were in danger during a lightning storm. The case studies were presented using site inspections after a lightning incident had occurred. However, the AVR method is not limited to cases involving livestock or wild animals. These cases provided useful research platforms without legal and ethical issues, which often surround research involving living beings.

The AVR thus provides an alternative to conventional lightning risk analysis methods, in defining the dangers associated with lightning injury mechanisms for any volume.

Further research to be considered includes:

- The concept of energy versus current as a killing mechanism of lightning strokes.
- The lightning impulse characteristics of tissue and organs of livings beings.
- The current paths through the human body during a step potential.

Appendix A

Reported lightning injuries

> Lightning statistics and information relating to incidents have, in the past, generally only been made available through the press. Eye witness reports are, at best, sketchy in their interpretation of events. This has made it difficult to identify the mechanisms associated with lightning injuries or fatalities. As more research has been performed and experts have been involved in investigating the scenes, a better understanding has been obtained and methods to reduce exposure to dangerous events have been developed. A greater understanding has also been gained in the interaction of lightning currents and the bodies of living beings. This appendix highlights a number of lightning investigations that have occurred over the last 60 years. They have been conducted by researchers from different fields, primarily being the engineering, medical and health sciences.

The number of investigations that have been performed are not in any way limited to the investigations presented below. The work is ordered in an approximate chronological order associated with the date of the event, though in some cases the reporting only occurred a number of years later. The reports consider a wide variety of incidents, in some of which only injuries resulted; this is to highlight the random nature of the lightning incident, and to demonstrate that what appears to be known does not necessarily hold for all cases.

In 1951, in East Africa, a church being attended by 300 people, was struck by lightning. Approximately 100 people were rendered unconscious, but only 6 people were killed (Cwinn & Cantrill (1985)).

Kitagawa (2000) describes three lightning cases that occurred in Japan over a number of years. Over a 30 year period, he has been involved in approximately 70 lightning cases involving humans. The first case occurred in 1967, when a group of school children were hiking in the Japanese Alps. 11 of the children were killed in the event. There were 46 people in the group and they were located near a peak on the trail when lighting struck the peak. It was determined that the lightning strike created a surface arc, which traversed the northern ridge, where a number of children were walking. 9 of the children died from electrical injuries, and the remaining two as a result of falling off the mountain. 9 members of the group were injured during the strike. An additional two cases involving climbers are presented, where it is believed that a surface arc occurred. In both of these cases, no fatalities occurred. Extensive burns were recorded in both events, with one unconscious person, a number of paralyses, some hearing loss, but all recovered within two weeks, with no sequela.

In the case of lightning incidents without surface arc flashover, Kitagawa presents three cases. The first case involves 15 people, resting from work near some trees in a suburban area. The centre tree was struck, which resulted in flashover to 2 women sitting near the tree. The remaining people were not severely affected by the strike, and were treated as out patients. The two women remained in hospital for approximately 2 months. 1 person was lying parallel to the developed ground potential and experienced momentary paralysis on the right side of their body, but no long lasting effects. In the second case, a first base umpire in a baseball game was directly struck. CPR was immediately given, but he was pronounced dead on arrival at the hospital. A player near the umpire received a shock, but no injuries. Kitagawa emphasises here, that a person near to another person struck directly, received no injury from a developed ground current. Two comments on this; firstly the orientation of the person is obviously critical in order for a step potential to be developed. Secondly, because of the nature of sports fields, the probability of some form of buried service, particularly water pipes for irrigation, could reduce the earth resistivity and, therefore, reduce the ground potential rise dramatically.

In the final case, in another baseball game, a player was running to second base, when the second baseman was directly struck by lightning. Rain had not started to fall yet. The second baseman died, almost instantly. The runner lost consciousness, but recovered 5 minutes later, and was provided with medical care at a hospital, with no sequela. Kitagawa indicates, again, that a person near another person who was struck directly received no real injury and survived the event. Again in this case, the service infrastructure buried in the field is unknown. Secondly, if the player running to second base was really running, invariably it means that only one foot was in contact with the ground, therefore a step potential would not have been experienced. The only mechanisms of injury possible would have been side flash, blunt or barotrauma or upward streamer.

Myers reports on an incident in the 1970s, where 47 people took shelter under trees during a storm. The age of the victims were between 3 and 21 years old. Lightning struck a tree, and 16 children were knocked to the ground. 1 child died as a result of extensive brain damage, myocardial infarction and second-degree burns. The child was initially resuscitated from cardiorespiratory arrest. A second child was rendered unconscious, had burns to both legs and abdomen, and developed department syndromes. She developed seizures and, eventually, required full time care because of resultant neurological damage. A third child had burns from clothing ignition, and demonstrated flaccid paralysis and absent reflexes of both legs. Recovery occurred, but the child had to walk with braces (Cwinn & Cantrill (1985)).

On June 4, 1978, lightning struck a group of three doctors, enjoying a Saturday afternoon with their families, at a leisure park (Jackson & Parry (1980)). They had taken shelter under a tree. There were 5 adults and 3 children in the group, but only 3 adults were injured. The first victim was holding a baby in his left arm, and an umbrella in his right hand. The baby was unhurt. He suffered paralysis of both legs and his right arm, as well as respiratory difficulties. His shirt was ripped, and he had first degree burns on his right arm and shoulder, and singed hair on his chest and left leg. An exit burn was noted on the lateral aspect of his right foot, and on his shoe. His right tympanic membrane had been completely destroyed. The second victim initially had total paralysis, and shortness of breath. This disappeared, but paraesthesiae developed, initially in his right arm, and then in both legs. Chest pain developed some moments later. Singed hair was seen on his right arm and leg, with an exit wound on the lateral aspect of the right foot. He was discharged after 5 days and, after a week, he still had some weakness of grip and dorsiflexion of his left foot.

In the autumn of 1980, at a soccer game of fifth and sixth graders from two schools in Illinois, USA, a lightning strike occurred (Dollinger (1985)). The first half was played in a slight drizzle, but the half time went on for about 30 minutes to allow for a thunderstorm to abate. A strike to the field knocked all the kids to the ground, as well as a few of the spectators. 3 children were unconscious. A number of children, including the three unconscious ones, were taken to a nearby hospital. A child, believed to have been struck by the lightning, was flown to a hospital in St. Louis. This child gained consciousness, but died a week later. Of the injured children, no lasting physical affects were noted, but many suffered psychological trauma, including sleeping disorders, high anxiety, fear of inclement weather, and separation anxiety. A child who has no memory of the event, but it was believed that a side flash occurred to him, was hospitalised for depression, as well as eating disorder, limb and back pain, fatigue, difficulty in concentrating, and episodes of crying.

In one case, a person struck by lightning had no cutaneous injury until 10 days later. They then developed necrosis of the pedal skin that required skin grafts (Cwinn & Cantrill (1985)).

Over a period of 17 years, Ohashi investigated a number of lightning incidents, with particular interest in the survival rate of victims if a flashover had occurred versus if it didn't (Ohashi *et al.* (1986)). In the analysis, there were 44 lightning strikes assessed, and a total of 140 victims. Of this group, 50 showed signs of current flow through the body. The 50 were divided into those whose clothes had been torn or ripped (9) and those whose clothes showed no visible signs (41). 55.5 % survived in the first group, as opposed to 14.6 % in the second group. Ohashi performed experiments with mice and rats, where two groups were created. A group with all their fur, and remaining dry, and a group which were shaved and had their bodies moistened with isotonic saline. The tests confirmed that the survival is more likely in the case of surface arc flashover. This occurred, in most cases, with the second group of rats. However, in some cases, no markings on the skin occurred, though flashover did occur.

On the 3 June 1987, ten soldiers were involved in a lightning strike during basic training, in Georgia, USA (Epperly & Stewart (1989)). The age of the group ranged between 17 and 35, with a mean age of 22.2 years old. Protection from the rain was sought under an oak tree. A strike to the tree occurred. No victim lost consciousness, but two soldiers suffered short term amnesia. Of the 10, 9 had dermal burns and abrasions. Dysesthesias (impairment of sensation) in extremities occurred in 8 soldiers. Minor orthopaedic complaints were noted in 4 soldiers, with 2 having headaches, and 2 with chest pain. All soldiers showed signs of focal musculoskeletal tenderness. 6 soldiers, during observation, were noted to have electrocardiographic ST segment elevation, which resolved naturally after 12 hours. Only 2 soldiers showed signs of tinnitus and hearing deficits. Metallic objects in their pockets were damaged. All soldiers remained under care and monitoring for 72 hours, and after 1 week all returned to full duty.

A 25 year old man was thrown off a tractor after being struck by lightning (Herrero *et* *al.* (1995)). The man was unconscious, but all other vital signs were good. The man had a traumatic injury of the scalp, without a burn, a superficial fern-like burn on the flank, and a deep linear burn affecting the neck. The burn on the neck was caused by a silver necklace which had been melted. His left ear had a ruptured tympanic membrane. He gained consciousness 2 hours after admission to hospital and was discharged two days later. The melting point of silver is 960 °C, which must have been reached by the flashover of the lightning across the man's body. This wound was the most dramatic injury received by the man and, once fully exercised, the wound healed.

Two cases were reported for Austria, at the 2006 ICLP conference (Kompacher *et al.* (2006)). The first involved a 25 year old man who was alpine walking when a storm occurred. The man had two aluminium walking sticks with him. It had not begun to rain and a lightning strike, directly to the man, occurred. Via the local lightning detection network, it was determined that the peak return stroke current was -4.8 kA. He had a puncture wound on the back of his left hand and, when he was found, he had blood coming out of his mouth, ears, and nose. There were no visible signs of external flash over, so it is assumed that the body was subjected to the entire lightning current. What is described as melting points on the walking sticks were observed.

In the second incident, a 50 year old female cyclist was walking home with her bicycle, after the bicycle's chain had broken. An eyewitness, who happened to be driving past, saw the woman being struck by lightning. The woman's helmet had cracked, and a piece of it was found approximately 50 m away from where she had been thrown to the ground. A gold necklace she had been wearing vaporized, and her shirt indicated burn marks around the neck and chest area. A 14 cm long injury (cut) was noted on her neck, the current is thought to have passed over her, and onto the bicycle, and flashed over the tyres to the ground. At this point, pieces of the asphalt were missing. The best approximated strike to the location and time was a strike with a magnitude of -6.4 kA. This woman survived the incident.

Gomes *et al.* (2006) investigated a scene where a lightning strike occurred during monsoon season in Bangladesh. The day of the incident was sunny, with afternoon convective thunderstorm development. The event occurred at a project site, where people had taken refuge under shelters with roofs made of galvanised iron sheets. A strike occurred approximately 3 m from one such shelter, with approximately 100 people under it. People were affected up to 150 m away from the strike point. There were 40 injuries and 3 deaths at the time of the strike. On the way to hospital, an additional 4 people died, and one day later, another person died. Of those injured, some stayed in hospital for up to 10 days. Most people injured complained of severe headaches, hearing problems, burn spots on legs and head, and some had partial paralysis of the lower limbs. One person was admitted to hospital, a number of weeks later, as a result of his injuries.

Berger (2007) presents two cases, the first in Paris, France. A young man, aged 24, was killed by a strike believed to have attached to a metal gate, approximately twenty metres from the victim. The second, was a 13 year old boy who was killed while playing soccer with friends. This occurred near lake Geneva, Switzerland. The lightning strike attached directly to the boy. Light rain had been falling but, until that strike, no lightning or thunder had been witnessed.

A 13 year old boy lost consciousness, directly after a nearby tree was struck by lightning (Saglam *et al.* (2007)). Medical emergency personnel, on arrival, found him unconscious and exhibiting signs of ventricular fibrillation (VF). Cardiopulmonary resuscitation (CPR) was started, as well as defibrillation in the ambulance. The VF deteriorated into asystole because of defibrillation. When he arrived at the medical facilities, he was pulseless and apneic. Advanced cardiac life support was given on arrival, as well as the administration of epinephrine and atropine, which, after approximately 10 minutes, converted cardiac rhythm to sinus rhythm. Physical examination revealed no burns, and pulmonary, abdominal and cardiac systems were all normal. A cardiology consult was performed and, though the coronary arteries were normal, there was an existing anomaly of the circumflex artery (Cx), that emerged from an independent ostium from the right sinus valsalva. There was no vasoconstriction, muscular bridge, plaque or thrombus in the right coronary artery or Cx. Myocardial damage, as a result of high energy transmission through the myocardium, prevented ventriculography from being performed, as arrhythmogenic effects can result. The patient was moved into an intensive care unit but, despite all measures, the patient died after 24 hours of medical care.

In another case, of an 11 year old child who was being the goal keeper in a soccer game, it is assumed that the goal post got struck and flashover occurred to the child (Murty (2007)). He arrived at the hospital unconscious. An examination of the child revealed surface burns to the face, neck and trunk areas. The lightning current passed through the lower left limbs and resulted in bursting of the left foot. The shoes had been torn, but were removed in the field to allow for access to the wound to control the bleeding. The computed tomography (CT) scan showed signs of cerebral edema. He also had swelling of the ear, eyelids and lips. The boy spent 1 week recovering in hospital. Intense edema of the skin was seen at the point of entry of the current, it is believed that this is due to paralysis of local capillary and lymphatic vessels. The exit wound that was on his left sole, is noted to not to be common in lightning injuries.

In Kuala Lumpur, a labourer walking home, was struck by lightning. The roadside, where he had been walking, had tall trees growing alongside it. He was struck on the right side of his body, and was taken to PPUM hospital, Kuala Lumpur, but was pronounced dead on arrival (Murty (2009)). His clothing was burnt, torn and disarranged. His right eardrum was ruptured with blood collection inside. His left eardrum was intact. All organs were congested, and his brain was severely oedematous and showed congestion. There was also tonsil herniation in the medulla oblongata. Haemorrhages were seen on the lung, as well as the intestines. The liver surface was hardened, and the substance underneath was coagulated and congested. The spleen surface was also coagulated and hardened, the underneath substance showed intense congestion. Histology of the organs showed intense heat and current effects. Most of the organs showed coagulation necrosis, haemorrhages, swelling and disruption of fibres. The disruption of the clothes and burn marks seen on the skin indicate that there must have been an arc over the body as well as current flow through the body.

Two lightning cases are presented where the lightning injury predominantly affected the spinal cord (Lakshminarayanan *et al.* (2009)). The first case was a 39 year old man who was struck by lightning and suffered a loss of consciousness and second degree burns to 4.5 % of his body. A magnetic resonance image (MRI) of the brain revealed the presence of a left thalamic and basal ganglia hemorrhage. He was noted to have right hemiparesis, as well as hemisensory deficits. A month after the incident, he underwent intense rehabilitation therapy. Three months after the injury, numbness and tingling in the arms and legs were experienced. Neurological exams showed a normal mental status and cranial nerve examination, except for mild dysarthria. Power testing revealed weakness on the right hand side. The man had difficulty walking unassisted. Over the following five years, gradual improvements were seen, though difficulty was still experienced in running and jumping. Nerve conduction studies at three months revealed the absence of N13 on all responses beyond that, indicating a conduction block at the cervical spinal cord (C5). An MRI of the cervical and thoracic spine was performed three months after the injury and showed a diffusely abnormal cord from C1-C6, without enhancement. An abnormal signal within the posterior aspect of the cord was present, from the the superior aspect of the odontoid to the mid C6 level, without cord compression. A follow-up MRI, performed more than four years later, showed no abnormality in the cervical spine.

The second case was a 47 year old man. As he alighted from his car, during a storm, he remembers a flash of light, and then he collapsed (Lakshminarayanan *et al.* (2009)). He experienced weakness, numbness and coolness in his legs, and was unable to walk unaided. There were no complaints about the bowel or bladder. It was also found that the car would not start, as the electrical system was not functioning. Neurological exams revealed normal mental status and cranial nerve function, there were superficial burns on the left leg and foot. Muscle stretch flexes were normal in the upper body, but not in the legs. Cerebellar function tests proved to be normal. He developed brisk muscle stretch flexes in his legs over the next 48 hours. This was more severe in the right than the left.

In the first case, demyelination may have been the pathophysiologic mechanism of lightning injury to the cervical spinal cord. The intense rehabilitation performed post the event helped in the recovery. In a separate incident with the same findings, death resulted three months after the event (Lakshminarayanan *et al.* (2009)). The second case suffered an acute insult to the spinal cord, causing weakness and paresthesias immediately after the lightning strike. The patient exhibited features of keraunoparalysis (KP). However KP is generally a short term feature, unlike the symptoms presented in the second case, which lasted for weeks. The neurological symptoms aligned most closely with traverse myelitis, involving the upper lumbar segment of the spinal cord. There are few reported cases of spinal cord injuries and classification of these injuries and subsequent treatment. In some cases, if left unattended this may result in death.

In India, a 16 year old farm labourer had a lightning strike attached directly to his head (Wankhede & Sariya (2012)). He was found in an unconscious state by his co-workers. He had respiratory difficulties, his shirt was torn in places and underpants were soiled. The autopsy was conducted 18 hours after death. Scleral haemorrhages were present in both eyes. No damage to either ear was seen. Second degree burns were found on the supertrasel notch and the lateral aspect of the right upper thigh. First degree burns were found over the sternal and epigastric region, and comprised 9 % of the body. Singeing of body hair was only seen over the chest and pubic region, as well as the medial aspect of the left lower limb. The tongue was oedematous and the papillae were scorched. There was congestion of all the major organs and oedema of the lungs. The mucosae of the pharynx, epiglottis and larynx were congested and oedematous. Ecchymotic areas were found in the retropharynx, the wall of the oesophagus, and adventitial tissue between the trachea and the oesophagus. In the oesophagus were multiple longitudinal mucosal tears along its entire length, up to the gastro-oesophageal junction. The tracheo-bronchial tree tract was congested and contained white froth.

Blumenthal (2012*b*) reports a first recorded incident where a 48 year old woman was killed by lightning, but, on examination, showed signs of shrapnel injury. The ground near where the woman was walking was struck, and small pieces of concrete were blasted up and became embedded in her legs. The post-mortem showed that the cause of death could be aligned with that of a direct lightning strike. Her son and daughter were both knocked down during the incident but had no significant injuries.

Recently, in South Africa, two events have sparked a media frenzy which has highlighted the necessity for warning systems, and better lightning education among groups responsible for open areas. The first case happened on the 11 February 2013, when 4 girls walking home from school through an open field, were struck by lightning. All four girls were thrown to the ground, and it was reported that they lay there for approximately 45 minutes. They then got up and walked home. Three of the girls went to hospital, where two of them were treated and released. The third girl died in hospital 5 days later.

The second incident occurred on the afternoon of the 12 February 2013, at a public boys school in Johannesburg. During a cricket practice, a storm arose and some boys were placing the cover over the pitch when, eye witnesses indicate, two successive strikes occurred, most probably a single strike, with multiple strokes. Nine boys, aged between 16 and 19 years old, were injured and, with quick response from a father who is a trained paramedic, the boys who seemed to have had a cardiac arrest were given resuscitation (CPR). The boys were taken to a local hospital, where 4 were checked and discharged. Three boys who had been kept under observation overnight were discharged the following day. Two boys remained in high care for a number of days, and have both subsequently been released. Of the last two boys, one of the them is going through extensive speech therapy, physiotherapy, occupational therapy and specialist medical care as a result of his injuries.

A.1 Lightning incidents to animals

Many incidents of lightning fatalities involve wild and domestic animals. Reports, however, are generally only received for domestic animals, as they represent economic loss for farmers. These are generally claimed against insurance and, thus, some form of reporting or data capturing occurs.

In June 1972, an army helicopter, on a routine flight-training mission, reported a large group of dead animals in the Alaska range. On inspection of the site, it was found that there were 48 adult elk and 5 calves. Toxicology of the animals revealed no lethal substances had been consumed. It was deduced, through the presence of a Lichtenberg pattern where the animals had been found, that the cause of the death was as a result of a lightning strike (Shaw & Neiland (1973)).

In 2003, a lightning strike, to a tree near a pig enclosure, resulted in the death of one animal, and the paralysis of the hind quarters of another three animals. The final four pigs in the enclosure had some form of paralysis, but could move with aid. No other functions of the animals were disabled. No burn marks were seen on any of the pigs, and tympanic membranes were all intact. Findings in the autopsy of the three paralysed pigs all showed multiple fractures of the last lumbar vertebral body and first sacral vertebral segment (Alstine & Widmer (2003)).

In August 2008, 13 cows were killed by lightning in British Columbia, Canada. In September, 53 cows were killed by a lightning strike in Katosi, Uganda. The cows were taking shelter under a tree, during a storm. Finally, in October, 53 cows were killed when lightning struck a fence next to where they were standing. This event happened in Valdez Chico, Uruguay (Dickson *et al.* (2012)).

In January 2012, two critically endangered eastern bongos (*Tragelaphus eurycerus isaaci*) were killed by a lightning strike at the National Zoological Gardens, Pretoria (Grant *et al.* (2012)). A tree, that the animals were taking shelter under, was struck, and this gave rise to a lethal step potential. The development of a flashover to the animals could not be confirmed, as there were no singe or burn marks on the animals' pelts.

In November 2012, 21 cattle were killed on a farm near Middleburg. This will be discussed in chapter 8, as a case study, following an investigation of the site. In the same geographical region of South Africa, in February 2013, 29 cows were killed from a lightning strike.

In December 2012, 5 wild horses were killed during a thunderstorm in Kaapsehoop, South Africa. 9 horses had gathered under a tree as the storm approached. A loud crack had been heard by some of the locals and, on investigation, they found five horses lying under the tree. The other animals had run away. The story was reported on *www.news24.com/SouthAfrica/News*, 10/12/2012.

A.2 Conclusion

In this appendix a number of reported lightning incidents have been presented. These show that in spite of what is known regarding lightning interactions with living beings, the results are not always as expected. Slight differences between similar events can mean the difference between an injury or a fatality. These reports indicate the difficulty of developing risk analysis methods because of the differing parameters in each case.

Appendix B

Risk methods

Risk methodologies and the application of IEC 62305-2 can produce a variety of results. This is primarily because of the level or depth of the assessment being performed. In this appendix the risk analysis methods, as well as results from a number of simulations, are presented. These analyses were based on three residential structure types typically found in South Africa.

B.1 IEC 62305-2 Risk analysis equations

To determine the total risk for a particular scenario, the first requirement is to determine the type of risk being assessed. In most cases it will either be the risk of loss of life (R_1) or the risk of economic value (R_4). Risk type R_1 comprises of the following risk components.

$$R_1 = R_A + R_B + R_C^* + R_M^* + R_V + R_U + R_W^* + R_Z^* \tag{B.1}$$

* Indicates cases where the failure of internal systems may result in the death of a living being, either by the failure of equipment or via explosion.

where:

R_1 Risk of loss of human life

R_A Injury due to step and touch potentials inside a structure and up to 3 m outside, as a result of a direct strike to the structure.

R_B Physical damage as a result of a direct strike to a structure which, as a result of sparking, may also result in fire and explosion.

R_C The failure of internal systems, as a result of a lightning electromagnetic impulse (LEMP), from a direct strike to the structure.

R_M The failure of internal systems, as a result of LEMP, from a nearby strike to the structure.

R_U Injury caused to a living being as a result of touch potentials from a direct strike to a service entering a structure.

R_V Physical damage as a result of sparking between internal components which may result in fire and explosions, as a result of a strike to a service entering the structure.

R_W Failure of internal systems caused by overvoltages, as a result of a direct lightning strike to a service entering a structure.

R_Z Failure of internal systems caused by overvoltages, as a result of a nearby lightning strike to a service entering a structure.

Risk type R_4 comprises of the following risk components:

$$R_4 = R_A^* + R_B + R_C + R_M + R_U^* + R_V + R_W + R_Z \tag{B.2}$$

* Indicates where the loss of livestock constitutes an economic loss, typically associated with agriculture.

The equation B.2 provides a typical risk value, but, in order to provide a monetary value to the analysis, additional equations are required. These are defined as:

$$C_L = (R_A + R_B) * C_A + (R_B + R_V) * (C_A + C_B + C_S + C_C) + (R_C + R_M + R_W + R_Z) * C_S \tag{B.3}$$

$$C_{RL} = (R'_A + R'_B) * C_A + (R'_B + R'_V) * (C_A + C_B + C_S + C_C) + (R'_C + R'_M + R'_W + R'_Z) * C_S \tag{B.4}$$

$$C_{PM} = C_P * (i + a + m) \tag{B.5}$$

$$S = C_L + (C_{PM} + C_{RL}) \tag{B.6}$$

$'$ Indicates the risk component value with the inclusion of protection measures.

Where:

C_L the cost of loss without protection measures in place

C_A the cost of animals

C_B the cost of the building

C_S the cost of the system in the structure

C_C the cost of the contents in the structure

C_{RL} the cost of loss in spite of protection measures in place

C_{PM} the cost of protection measures

i the interest rate

a the amortization

m the maintenance rate

S the annual savings with protection measures in place

Each risk component comprises of a number of different factors which are shown in *Figure B.1.* The factors relate to the nature of the structure, its surroundings and the services entering the structure. The parameters associated with the services include its height, length, location, surroundings and in the case of buried conductors, the earth resistivity. The relative location is also considered as this has an influence on the collection area for the structure and services. Factors associated with lightning protection measures, and safety features are also included in the standard, and these can be used to assess a structure where protection measures are already in place, or to provide a comparison of the total risk for a structure with and without protection measures in place. The loss components are probably the most difficult parameters to calculate. The generic values provided by the IEC are very broad based. However, to determine the losses as presented by the loss equations in IEC 62305-2, there must be comprehensive knowledge of the people present in a structure during a thunderstorm.

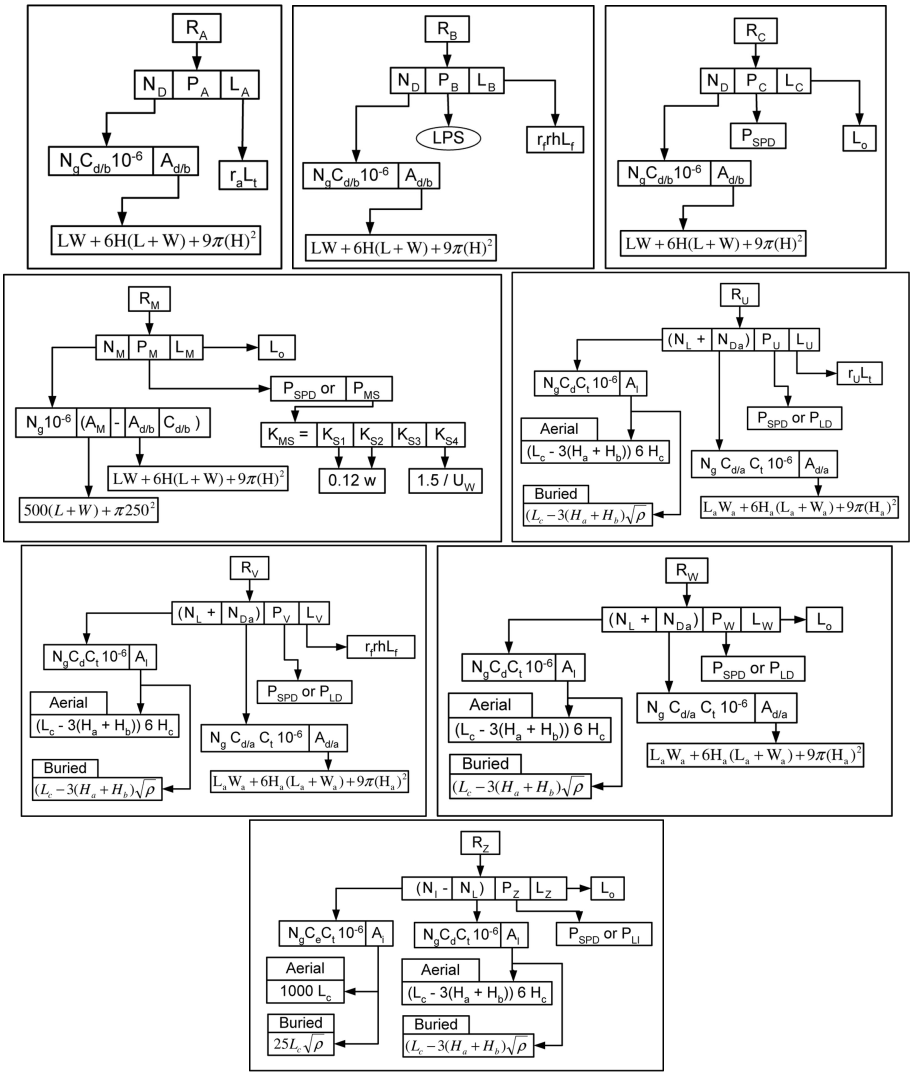

Figure B.1: Breakdown of the IEC 62305-2 risk components used to calculate the different risk types.

An investigation into the application of surge protection in a low voltage installation, in South Africa was performed (Dickson (2006)). Lightning risk analyses were performed on three different structure types found in South Africa. These structures were given the broad definitions of suburban, township and informal, and artistic representations are shown in *Figure B.2*. Each structure was defined and then placed in a number of scenarios, across the whole country; this included variations in location, service length and height, fire risk, protection measures, cost of electrical installations and equipment. General results from the work are presented in *Figures B.3 - B.9*. In *Figure B.9* it can be noted that the location of the structure shows very little variation between rural and suburban, it is only when it is located in an urban environment that the risk decreases. Some of the key advantages of a suburban/urban area are the effect the surrounding objects have on the collection area as well as the length of services attached to a structure.

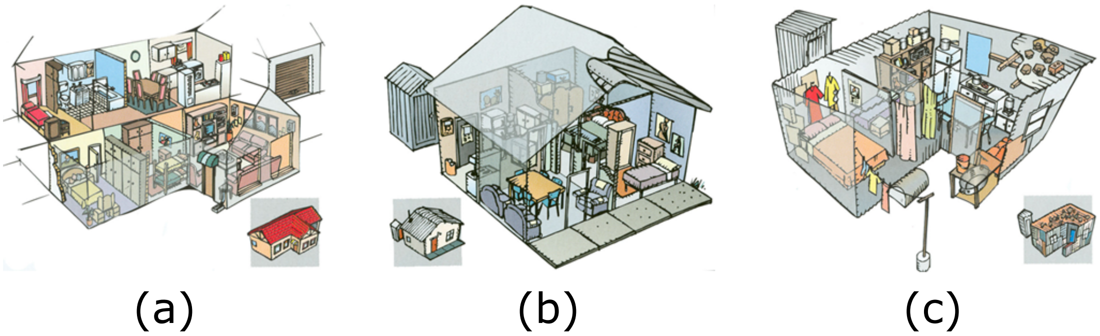

Figure B.2: Artist impression of the structures used for the lightning risk analysis study Eskom (1997). (a) Urban, (b) Township and (c) Informal

From the collection of scenarios performed during the analyses, it became apparent that a generalised graph could be created, taking into consideration the key parameters that influence the total risk for the variety of structures. *Figure B.10* shows a graph which relates the lightning ground flash density and the length and height of the service associated with a structure. These factors influence the total risk in any analysis and therefore this provides a quick application guide to the requirements of lightning protection measures. If a structure being analysed falls within a shaded area as a result of its parameters, then protection measures are required.

During the investigation, the process of analysing the township structure was, for the most part, inconsequential, as its risk was usually between that of an informal and suburban structure, providing little insight into the broader investigation. For the analyses for the risk of loss of life (R_1), it was generally seen that the informal structures

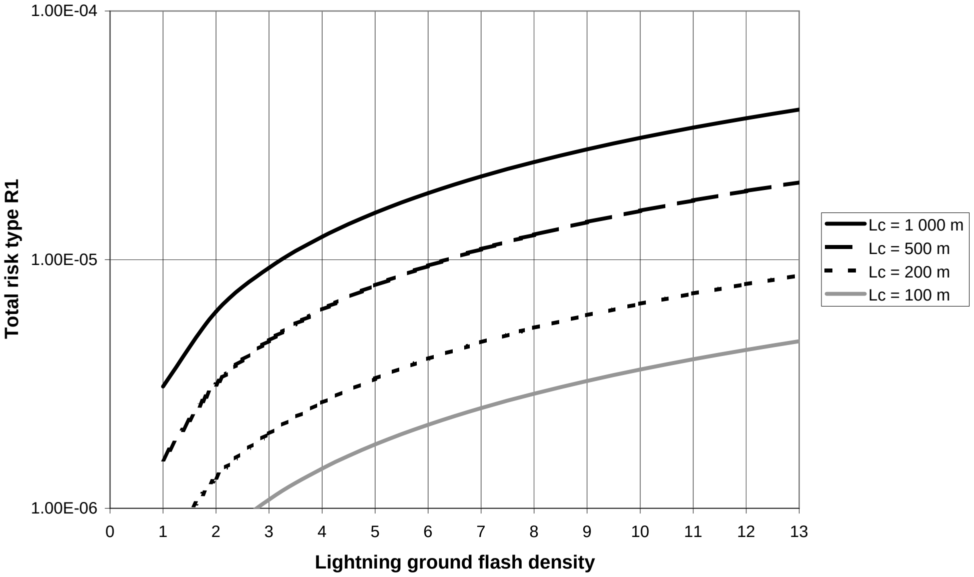

Figure B.3: Results of risk type R_1 for a suburban structure with a variable service length.

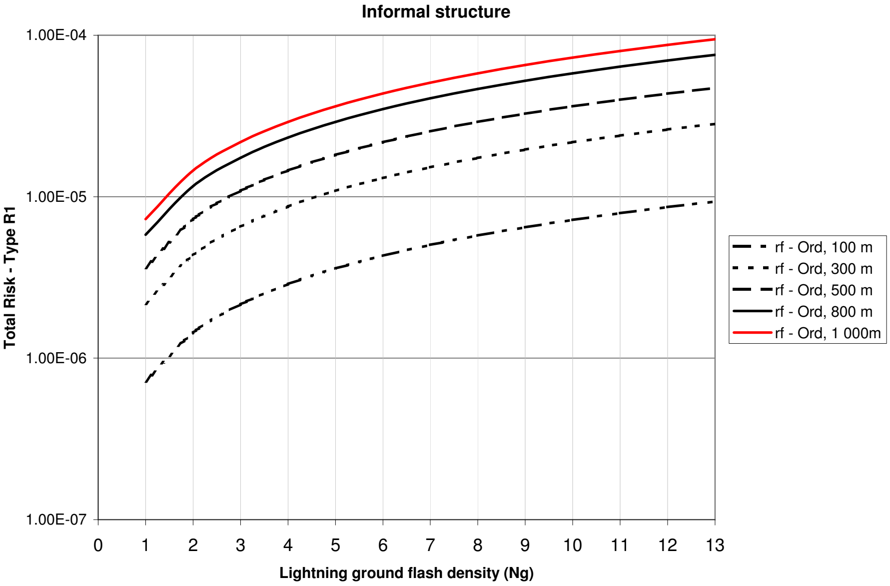

Figure B.4: Results of risk type R_1 for an informal structure with a variable service length.

had risks greater than the tolerable risk, mainly based around the length of service and the risk of fire within the structure. The suburban structure's total risk was less than the tolerable risk as the standards governing the structures make them inherently safe.

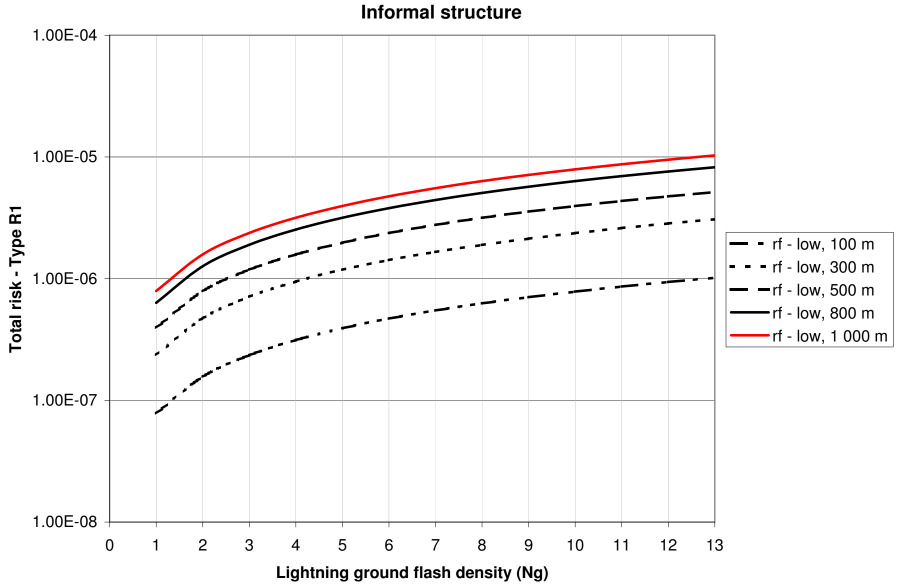

Figure B.5: Results of risk type R_1 for an informal structure with a variable service length, where the fire risk is low.

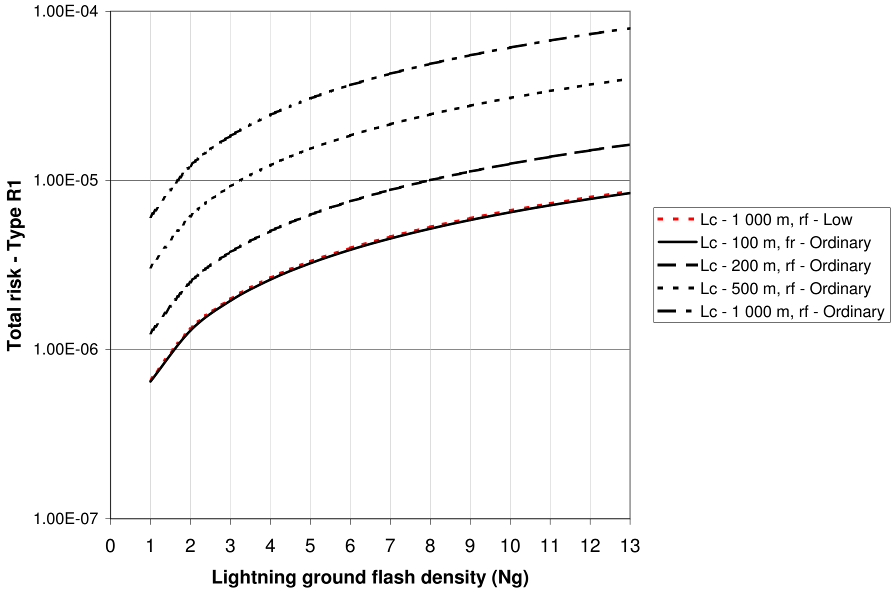

Figure B.6: Results of risk type R_1 for an informal structure with a variable service length, for a variety of fire risks.

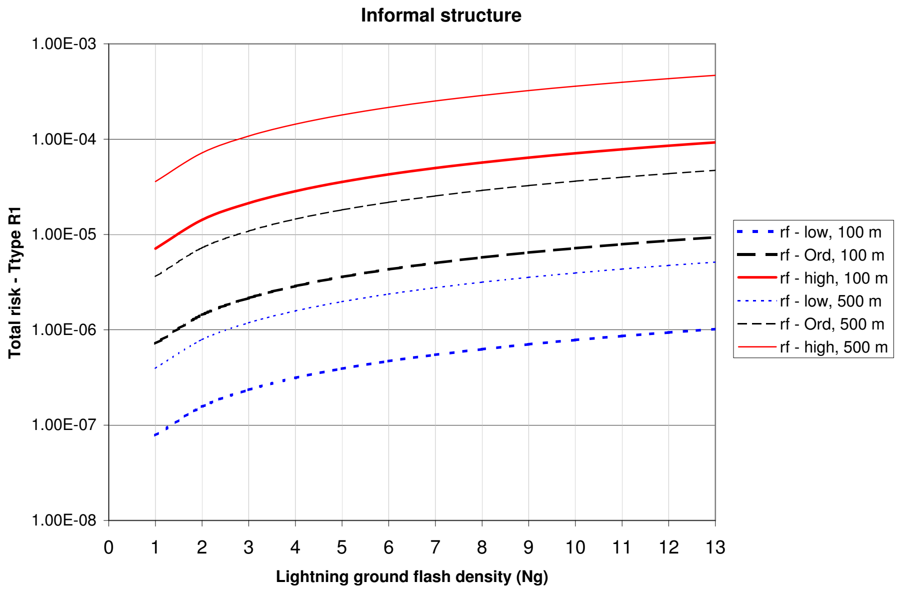

Figure B.7: Results of risk type R_1 for an informal structure with a service length of 100 and 500 m, for a variety of fire risks.

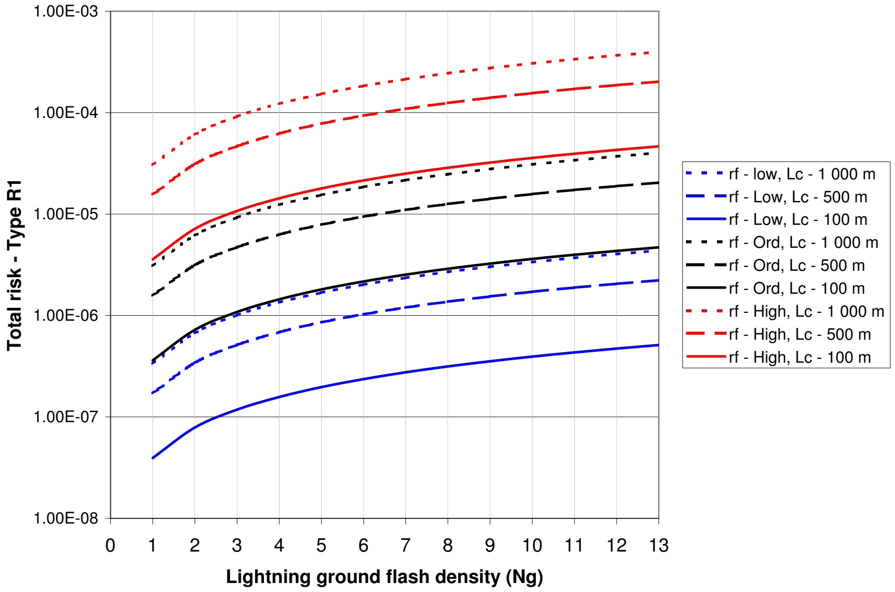

Figure B.8: Results of risk type R_1 for an suburban structure with a variable service length, with a variety of fire risks.

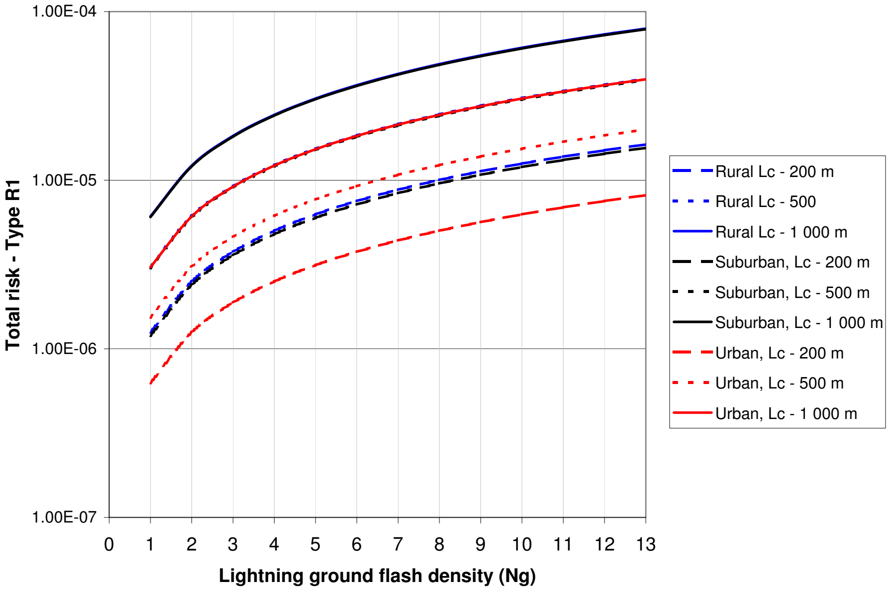

Figure B.9: Results of risk type R_1 for an informal structure located in different areas, with a varying service length.

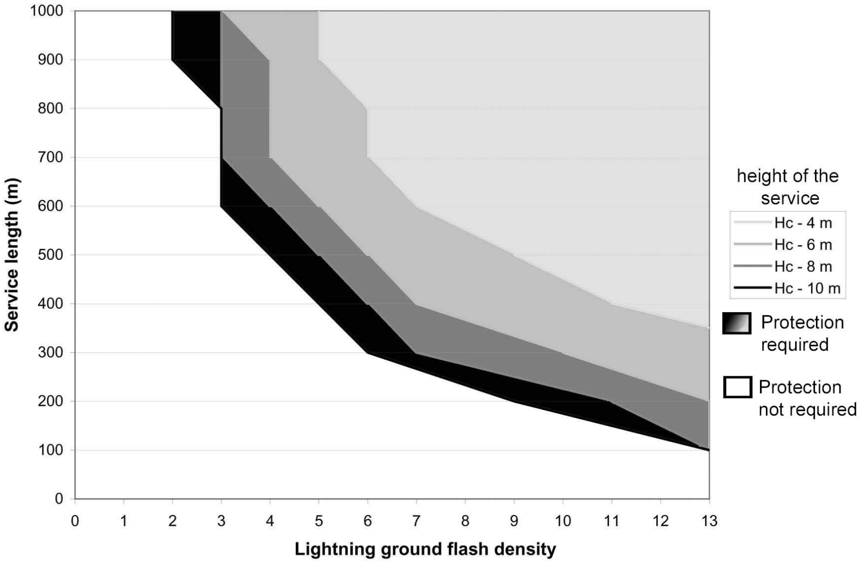

Figure B.10: Results of risk type R_1 for any structure dependent on the service length and height in relation to the lightning ground flash density.

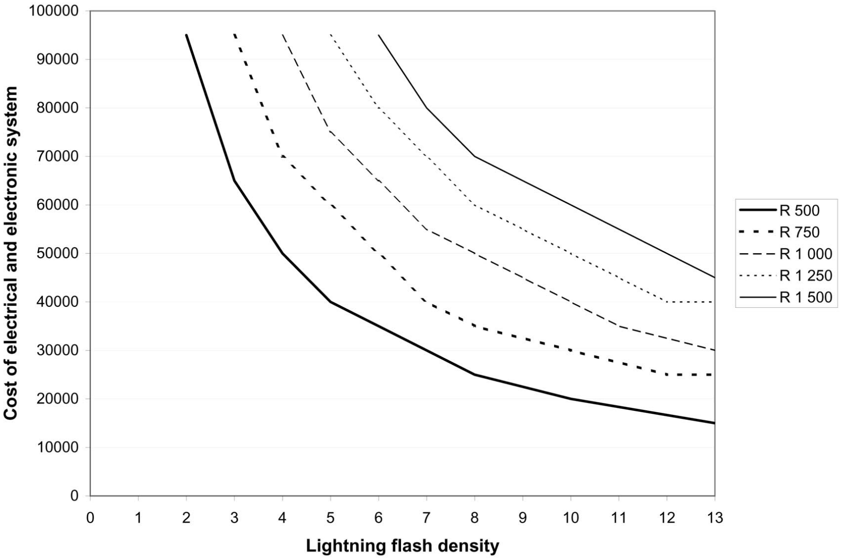

Figure B.11: Results of risk type R_4, based on the lightning ground flash density and the cost of the electrical and electronic system installed. If the structure falls to the right of a graph, then the cost of protection is associated with the graph immediately to its left.

This risk comes closer to the tolerable risk level as the lightning ground flash density increases above 10 flashes/km^2/year.

For risk type R_4, the risk of loss of economic value, the main area of interest was the suburban structure. Analysis showed that for informal and township structure, the relative cost of protection versus the cost of electrical and electronic equipment installed did not indicate a saving. For the suburban structure it was possible to develop a model that relates the relative cost of protection versus the lightning ground flash density and the cost of the electrical and electronic system installed in the structure, shown in *Figure B.11*. The process is similar to that of the graph produced for the risk of loss of life, discussed earlier. As an example, if a structure was located in an area with a lightning ground flash density of 9 flashes/km^2/year, the structure had electrical and electronic equipment to the value of R40 000, then protection measures to the value of R750 should be considered.

B.2 Conclusion

The risk analysis process provides insight into the governing parameters when assessing the lightning risk for a structure, using IEC 62305-2. The length of the services, height above ground and the risk of fire factor, all have a significant influence on the final calculated risk value. From the data is was possible to establish a relationship between the length and height of a service attached to a structure as well as the lightning ground flash density, to create a look up graph which provides the parameters for the application of surge protection devices. A similar relationship was created based on the cost of the installed electronic devices versus the cost of protection.

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