A STUDY OF POLE TOP FIRES ON 22KV WOOD POLE POWER LINES IN KWAZULU - NATAL

By

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A postgraduate dissertation submitted to the Discipline of Electrical Engineering at the University of KwaZulu - Natal in partial fulfillment for the requirements of Master of Science in Electrical Engineering.

The author hereby declares that this dissertation represents his own work, except where other authors works have been used, in which case the use thereof is referenced.

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I hereby declare that all material incorporated into this thesis is my own original and unaided work except where specific reference is made by name. The work contained herein has not been submitted for a degree at another university.

Signed: ____________________

A.K. Persadh

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ABSTRACT

The majority of Eskom's 22kV lines use wood as the support structure material. The economics of wood pole cross arms and their flashover withstand capabilities outweigh those of steel cross arms. However, wood pole structures are vulnerable to what is known as a Pole Top Fire. When insulators and wood cross arms become polluted, small and sustained leakage currents flow along the surface of the insulator and thereafter into the wood itself. This eventually leads to burning of the wood. Many of the 22kV lines traverse vast rural lands, going over people's path ways. If this fire is not discovered timeously, it can cause breakage of the relevant cross arm or the pole itself. A broken cross arm usually causes the outer phase conductor to hang between one and two meters above ground. When it's dark, rural inhabitants cannot see clearly and walk directly into these low lying energized conductors which cause severe injuries and often fatalities. Low hanging conductors cannot be detected electrically and are potentially hazardous to humans and animals. Safety is currently one of the highest priorities for Eskom Distribution and hence there is a dire need to mitigate Pole Top Fires. The researcher hypothesizes that the implemented mitigating technique of bonding does not eliminate Pole Top Fires.

In this study **accurate** statistics on Pole Top Fires in KwaZulu – Natal are provided and causes of fires investigated to provide an understanding thereof. Two basic mechanisms of burning have been identified and explained. These are surface tracking and sparking, and internal sparking. This has helped to explain what mitigation techniques will be effective. A critical analysis on the performance of recommended mitigation techniques is conducted. This study therefore aims to conclude on the effectiveness of implemented techniques to mitigate Pole Top Fires. By comprehensive and critical analysis of a complex operational and safety related problem technical options for mitigating or eliminating the fires are identified, critically analyzed and only those options that are really technically feasible are proposed. This has not been properly done in Eskom before. It is within this context that this research has been undertaken.

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

kV	-	kilovolt
°C	-	degrees Celcius
μ	-	micro
A	-	Amperes
mg	-	milligrams
%	-	percentage
cm	-	centimeter
NaCl	-	Sodium chloride
mm	-	millimeter
R	-	Radius
>	-	is greater than

ABBREVIATIONS

KZN	-	KwaZulu – Natal
D DT	-	Drawing Distribution Technology (now IARC)
IARC	-	Industry Association Resource Centre
FSA	-	Field Service Area
TSC	-	Technical Service Centre
CD	-	Compact Disk
DVD	-	Digital Video Disk
MVA	-	Megavolt Ampere
RLC	-	Reticulation Line Construction
ESDD	-	Equivalent Salt Deposit Density
IEC	-	International Electro – Technical Commission
Fig	-	Figure
RMS	-	Root Mean Square
AC	-	Alternating Current
Umax	-	Maximum supply voltage
KPLC	-	Kenya Power and Light Company
TSI	-	Technology Services International (Eskom)

TRI	-	Test, Research and Investigations (Eskom)
CSIR	-	Council for Scientific and Industrial Research
ERID	-	Eskom Research and Innovation Department
BIL	-	Basic Insulation Level
N/B	-	Network Breaker
PTF	-	Pole Top Fire
Km	-	Kilometer
E	-	Electric Field
APP	-	Air Pollution Potential

CHAPTER 1: INTRODUCTION

1.1 Background

Overhead power lines are designed and constructed so as to be electrically insulated from earth whilst distributing power. Wood and steel poles are the material that is used to construct power – lines in Eskom Distribution. A common element of Eskom Distribution's infrastructure is cross arms. Cross arms are basically used at the top of poles to suspend overhead conductors which distribute power.

The majority of Eskom's 22kV overhead lines use wood as the support structure material. Although the details of individual pole design vary from area to area, a feature common to the design used in KwaZulu – Natal (KZN) is the use of the wood cross arms to give additional inter-phase and phase-to-ground insulation (Britten, 1995). This method helps to improve their performance in high lightning areas. An example of such a design is shown in the picture below.

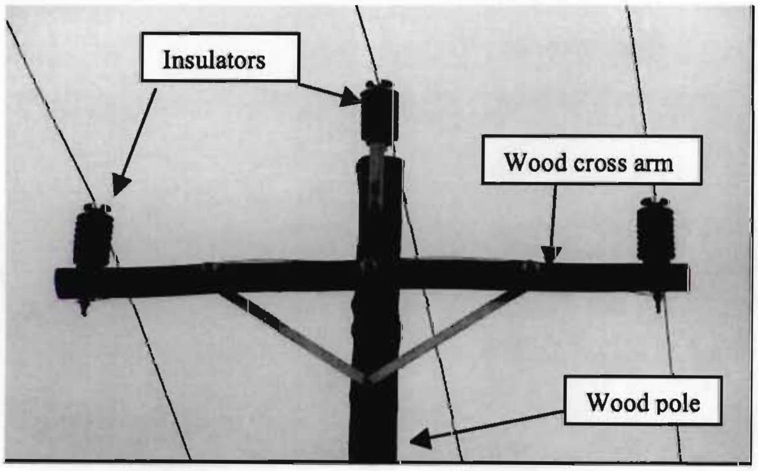


Figure 1 – 1: A common wood pole structure design (D DT 1740B).

The above design can be vulnerable to what is known as a Pole Top Fire. It is not the only design that is vulnerable. Other designs such as the verticals (D DT 1710 and D DT 1370), link structures (D DT 1848 and D DT 1849) and strain assembly structures, to name a few are also vulnerable to Pole Top Fires. These occur if high leakage currents flow along the surface of the insulator (if and when it becomes polluted and wetted) and thereafter into the wood itself by direct contact or by means of sparking. This is a well known problem in coastal areas where salt spray periodically creates the pollution necessary to allow high leakage currents to flow (Britten, 1996).

The practice of using wood as the inter – phase insulation has for many years been widely and successfully applied in Eskom and in most other countries where 11, 22 and 33kV overhead lines are used. If a Pole Top Fire is not discovered timeously, it can cause breakage of the relevant cross arm or the pole itself. A broken cross arm usually results in the outer phase conductor hanging low, without making contact with the ground. This is usually between one to two meters above ground level. This condition cannot be detected electrically and is the main reason why the consequences of Pole Top Fires are potentially hazardous to humans and animals (Britten, 1996). Figures 1 – 2 and 1 – 3 respectively illustrate this. Many incidents have occurred including a few human fatalities, resulting in huge financial losses to Eskom. Almost 600 cross arms on 22kV over head lines throughout KwaZulu – Natal have burned from January 2001 to January 2007.

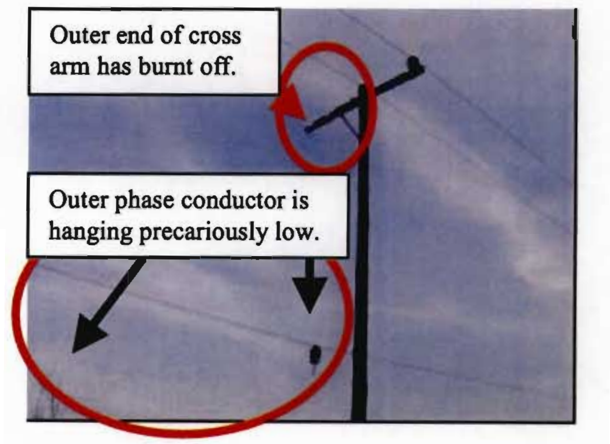


Figure 1 - 2: A burnt **cross arm** resulting in a low hanging conductor.

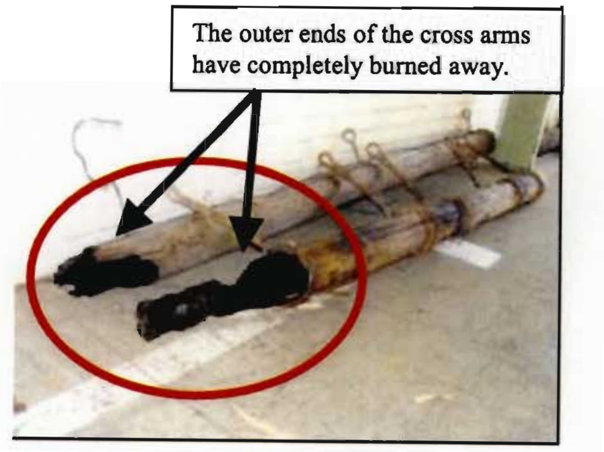


Figure 1 – 3: Extent of the damage (charring) at the ends of cross arms.

In Figure 1 – 2 above, the left of the cross arm has burned away resulting in the insulator and phase conductor hanging precariously low. Fig 1 – 3 highlights the extent of charring where the outer section of cross arms has completely burned away. This has resulted in that particular phase conductor either parting or hanging low which is of serious concern to Eskom.

1.2 Motivation

For Eskom, incidents of the above nature lead to legal, financial, safety and publicity risks and must be minimized or even eliminated while still providing affordable energy to its people. The researcher focuses on the basic mechanisms which cause burning which underpins the performance of Eskom Distribution infrastructure and hampers the business quality of supply.

In this study, the researcher provides statistics on the occurrence of Pole Top Fires in KZN. The researcher also investigates the causes of pole top fires and provides an understanding thereof. A critical analysis on the effectiveness of technically feasible mitigation techniques over the last decade is conducted. This study therefore aims to conclude whether or not the mitigating technique of bonding that was implemented in Eskom Distribution actually reduces or even eliminates Pole Top Fires or if fires can still occur because of the combined neutral shift phenomena and electric field. It was also believed that properly bonded structures will not burn. This assertion is investigated.

By analyzing a complex problem of this nature, possible and effective mitigation measures can be identified. This has not been properly done in Eskom before. The researcher also examines other technical alternatives to minimize Pole Top Fires and proposes only those that are really technically feasible. It is within this context that this research is being undertaken.

1.3 Outline of chapters

The background in the Introductory chapter introduces the wood pole structure for overhead power lines and highlights the phenomenon that it is vulnerable to viz. Pole Top Fires. The research problem contextualization is also addressed. The motivation includes the aims and the objectives of the study.

Chapter 2 highlights the extent of the phenomenon of pole top fires since the early 1990's. Accurate statistics for Kwa Zulu - Natal since 2001 are given and of which illustrate the seasonal patterns on 22kV wood pole power lines. The researcher also critically analyses the various initial designs implemented since the early 1990's and subsequently the different types of burning experienced. Chapter 3 forms the extensive part of the dissertation report, where the theoretical review of the study is highlighted in greater detail. It focuses on the mechanisms of burning and the controlling parameters thereof, field and laboratory investigations, bonding of line hardware and insulation co-ordination. An understanding of how and why pole top fires occur will also be discussed. Furthermore, the researcher explains why the phenomenon is common to KwaZulu – Natal although other areas use the same design of wood pole structures. Occasional fires do occur elsewhere in Eskom.

The research methodology used in the study is presented in the fourth chapter. Field work in terms of piloting and implementing Eskom standard structure designs and the monitoring of test sites thereof is addressed. A critical analysis of effective bonding is covered. Measures that were taken to prevent the phenomenon are discussed and evaluated.

The final chapter concludes by highlighting the researcher's findings and whether the objectives of this study have been achieved. In addition, the researcher forwards recommendations and provides an overall conclusion of the study.

CHAPTER 2: POLE TOP FIRES IN KWAZULU – NATAL

2.1 The extent of Pole Top Fires in KZN

Eskom field personnel in the Northern parts of KwaZulu – Natal have regularly complained of pole top fires. During the 1990's, the Nongoma, Mtubatuba, Hluhluwe, Kwambonambi, Pongola, Stanger and Empangeni areas have experienced extensive cross – arm failures on 11kV and 22kV overhead lines. The south coast of KwaZulu – Natal had also experienced cross arm failures in the early parts of January 1994. The failures were directly related to the burning of the wooden cross arm and sometimes the main pole (Loxton et al, 1996).

As a result, numerous injuries and fatalities amongst the local inhabitants have taken place because of undetected low lying conductors. These incidents which resulted in unsafe conditions to local inhabitants became a major concern to Eskom. Eskom has been involved in numerous legal claims in respect of deaths, severe injury and fatalities to both the locals and their livestock (Narsai, 2005).

The majority of the failures reported had occurred over the dry winter months peaking in September and October prior to the annual rains in November. However, once rain showers have washed the insulators on these lines, the number of failures had reduced. However, sporadic incidents still occur continually over the summer period (Ranjin, 2004).

In September of 1993, the Eskom Durban Distributor convened technical meetings to look into the abnormally high incidence of pole top fires in Northern KwaZulu – Natal. Approximately 78 fires had been reported in an 8 month period in that year. About 60% of these occurred in the Mtubatuba area. The remainder had occurred in areas which were further inland (Crossley, 1993). The occasional fire was reported in other areas where similar designs were used, example Southern Natal, Free State and the old Transvaal. Investigations by Britten in 1996 revealed that:

- All burnt cross arms were either un-bonded or poorly bonded.
- Dust and pollution had contributed to failures.
- 80% of the failures occurred during the dry seasons.
- Majority of the fires occurred in the Northern KwaZulu – Natal stretching from Mandini in the South to Mkuze in the North.
- The northern KwaZulu – Natal networks were exposed to high pollution from industries in Richards Bay.

Measures to mitigate the phenomenon have been introduced and implemented since the early 1990's (Hartman, 1994). However, due to poor management, time or financial constraints not all networks were covered in the implementation of the mitigation techniques. Hence the burning continued on those networks.

Accurate statistics of the phenomenon from the Eskom Distribution Plant Department have been collected and these are tabled below per FSA (Bouwer, 2006). The tables and graphs below indicate the number of incidents of pole top fires and the subsequent total MVA hours lost. These statistics indicate incidents on 22kV lines only and for all Field Service Areas (FSA's) within KwaZulu – Natal from January 2001 to January 2007 (Bouwer, 2006). The total line length per FSA is also included. Note from the table that the number of incidents in the Empangeni FSA is far greater than those in the other areas. When the statistics were collected from field staff, finer details as to whether cross arms were bonded or un-bonded were not ascertained. However, many of the networks are old and it is possible that these figures are mainly for un-bonded cross arms.

Statistics of Pole Top Fires on 11 and 33kV overhead lines for the same period are available and are very similar. However, the author is concentrating on the predominantly 22kV overhead lines. Hence statistics for 11and 33kV networks are omitted.

Table 2 – 1: Number of incidents of Pole Top Fires on 22kV wood pole lines in KZN from January 2001 to January 2007.

Year	Empangeni	Petermaritzburg	Newcastle	Margate	Totals
2001	54	4	18	9	85
2002	117	7	20	16	160
2003	74	4	12	11	101
2004	45	2	14	8	69
2005	77	4	25	13	119
2006	37	4	11	3	51
Jan 2007	3	0	2	2	7
Totals	403	25	102	62	**592**
Line Length (km)	65989.51	2944.54	15460.32	7985.43	**92379.80**

Table 2 – 2: MVAhrs lost in KZN due to Pole Top Fires on 22kV wood pole power lines from January 2001 to January 2007.

Year	Empangeni	Petermaritzburg	Newcastle	Margate	Total MVAhrs lost
2001	701.9	26.31	103.56	286.69	1118.46
2002	1775.7	39.06	126.71	184.92	2126.39
2003	860.61	9.39	73.29	96	1039.29
2004	610.68	18.12	163.33	175.15	967.28
2005	593.14	39.35	194.41	98.78	925.68
2006	340.53	8.95	230.09	19.52	599.09
Jan 2007	5.86	0	16.13	5.96	27.95
Total MVAhrs lost	**4888.42**	**141.18**	**907.52**	**867.02**	**6804.14**

The data was also filtered and consolidated into total number of incidents occurring per month. These were then tabled according to seasons. The graph below illustrates the seasonal pattern of Pole Top Fires from January 2001 to January 2007. Monthly and annual variations are also illustrated below.

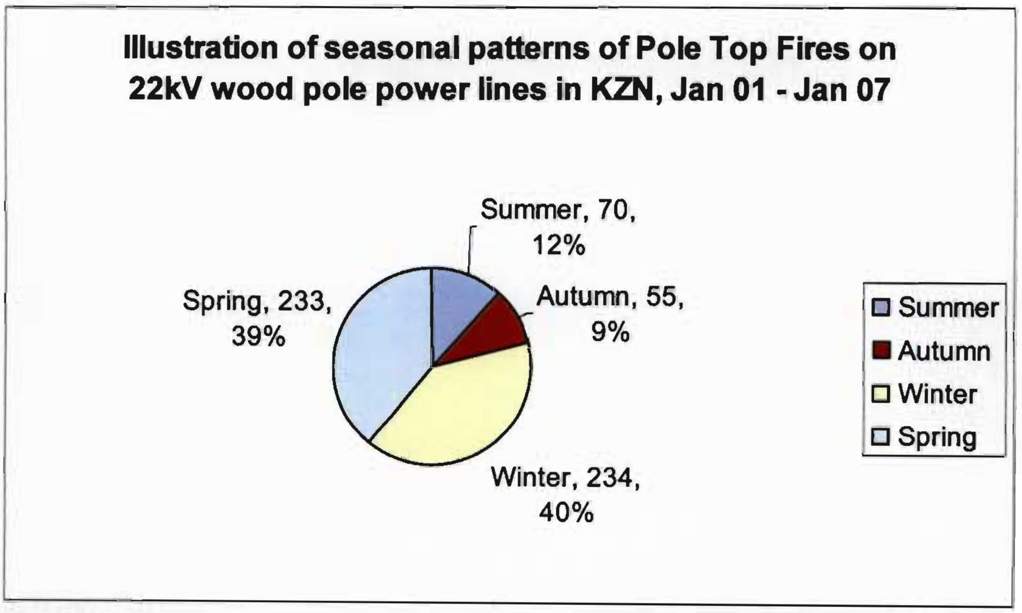


Figure 2 – 1: Seasonal pattern of Pole Top Fires on 22kV wood pole power lines in KZN

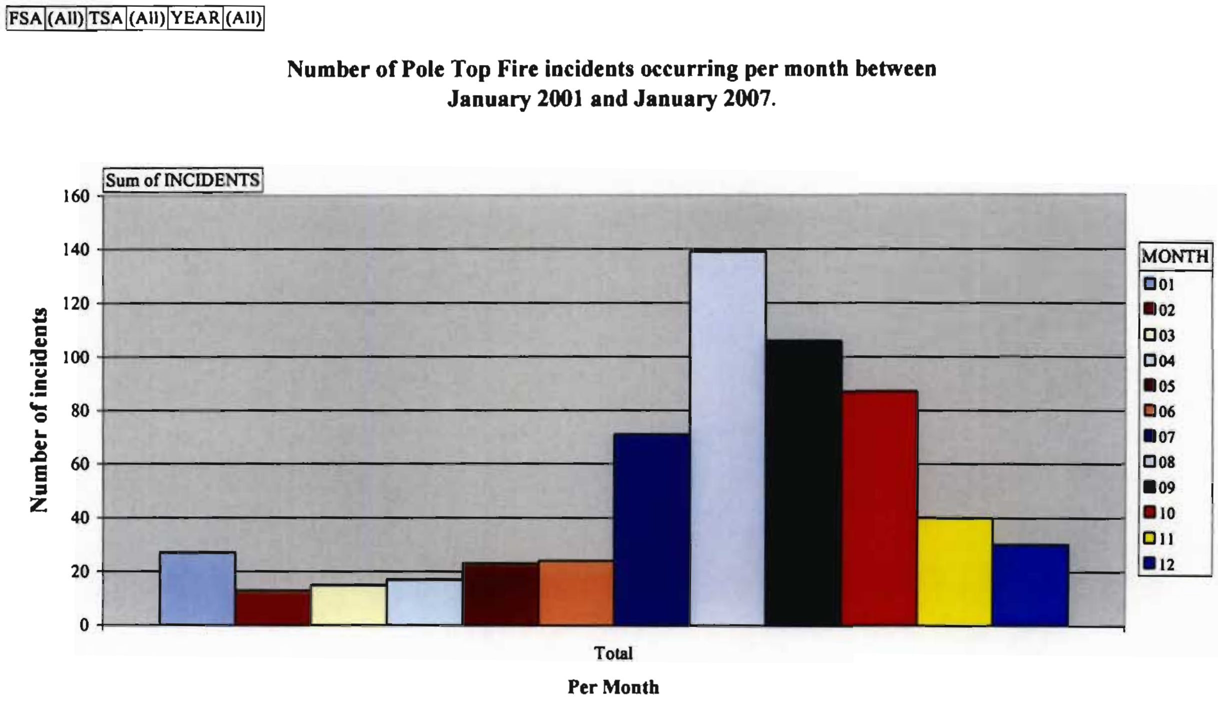


Figure 2 – 2: Number of Pole Top Fire incidents occurring monthly in KZN

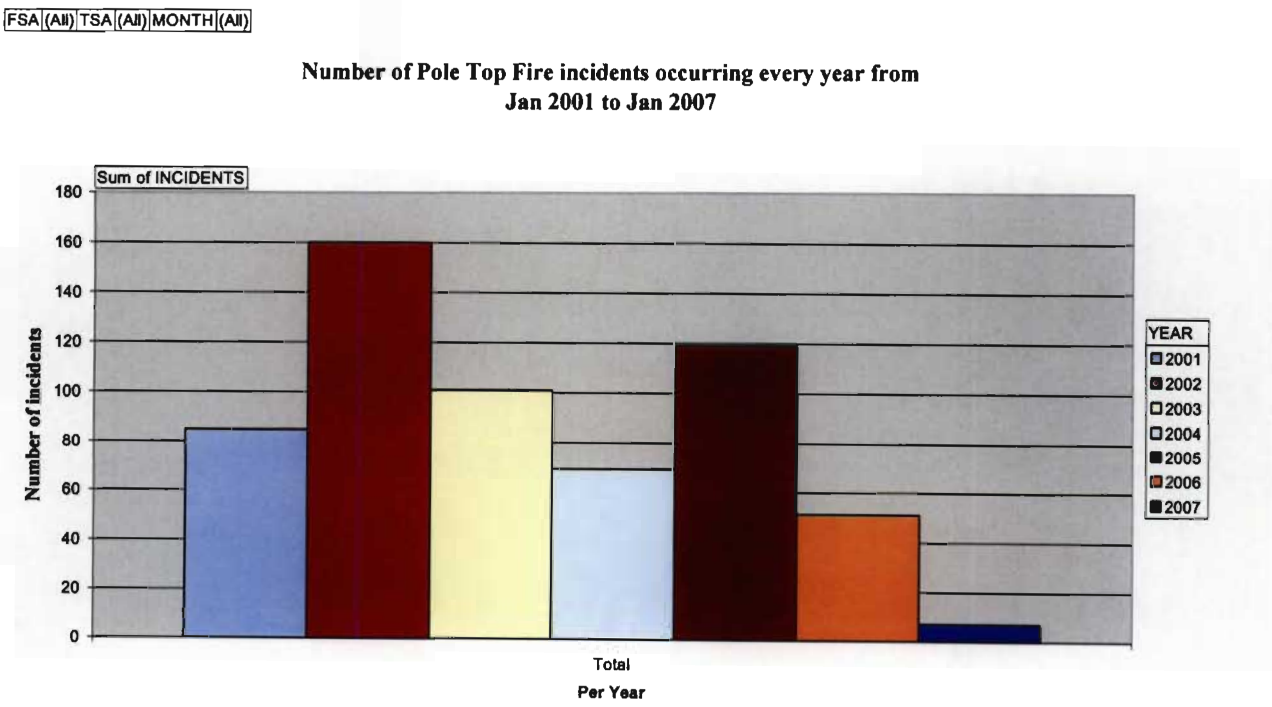


Figure 2 – 3: Figure showing the annual variations of Pole Top Fires in KZN

It is seen from the above figures that majority of fires occur in the winter months and extend far into spring. The reasons for the high failures during these months are explained in detail in chapter 3. The researcher will now examine the different types of burns experienced and will also speculate what the mechanisms of burning could be.

2.2 Various designs leading to different types of burning

It is known that the different types of burning that had occurred are a result of un-bonded structures or structures that were poorly bonded. It is a common belief in Eskom Distribution that such wood pole structures will eventually burn.

2.2.1 Implementation of Bonding in KwaZulu – Natal

Following many investigations on Pole Top Fires which were done in the early 1990's and also further research into the various mitigation techniques, Eskom Distribution decided then to adopt the method of bonding on all wood pole structures in northern KZN. The intention then was to reduce or even eliminate the cross arm burning phenomenon. This change or modification in technology required an effective implementation or change control plan. Bonding provides an alternative medium for leakage currents to flow away from the insulator and wood surface of the cross arm. In this technique, the bonding wire is not connected to earth and hence bonding is not the same as earthing.

The researcher is employed in the Technology and Quality department of Eskom Distribution in KZN since 1999 and has since been involved in various initiatives to ensure proper bonding on wood pole structures. While collecting the above statistics, various investigations were done by the researcher to ascertain reasons for the burning phenomenon. It must be noted that the examples given below have largely contributed to these statistics. The various practices since the early 1990's shall now be critically analyzed and the poor implementation thereof highlighted.

On 10 March 1993, an Eskom Engineering Instruction (RLC/10) was published by R.T. Green (Appendix A). This instruction was applicable to KwaZulu – Natal and gave explicit details on the bonding method to be applied. The materials consisted of three strands of copper conductor (3/104), galvanized steel washers and clips which were fastened by hexagonal nuts. Various retro – fitting exercises were put into place and effected to bond structures in the areas affected by the burning phenomenon. However, not all structures were bonded. To date there exist many structures that are still un – bonded and these structures have become part of the statistics associated with Pole Top Fires. Investigations by the researcher uncovered various non – conforming practices since 1993 and their shortcomings are highlighted.

2.2.1.1 Use of Solid Copper Wire

Prior to 1995, a common Eskom Distribution design included the double wrap binding wire method to strain off conductors via glass disc type insulators or long rod porcelain type insulators. This is illustrated in Fig 2 – 4 below. Notice the tracking at the mounting bolt of the cut out link on the opposite side.

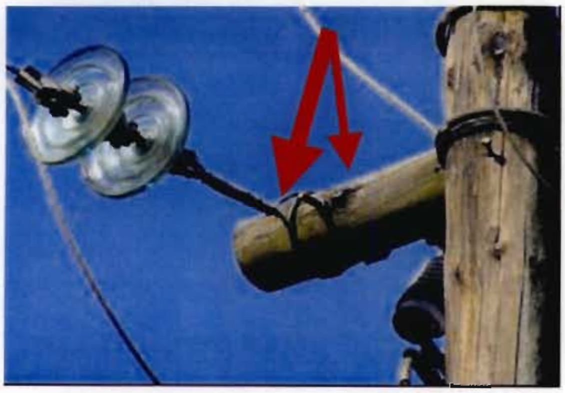


Figure 2 – 4: Application of binding wire to strain off conductor.

Many of the above type structures were 'bonded' via solid 4mm² copper wire. The method of bonding included passing the copper wire underneath the binding wire that terminated each phase conductor. This is illustrated below.

Figure 2 – 5: Illustration of solid 4mm² copper wire used for bonding.

As can be seen from Fig 2 – 5, the method has not worked since the cross arm is severely burned. This application was not as per the requirements of Engineering Instruction (RLC/10) that was published. In this type of installation, the leakage current flowed in both the copper wire and surface of the cross arm. Not all current was diverted away from the cross arm surface and those that did flow onto the surface caused the ignition. Also, there is a very poor electrical connection between the binding wire and the copper wire. Hence, this type of bonding could be considered as poor bonding as there is sufficient evidence that it has not worked and that is the burnt cross arm.

Other designs also included metal based post ceramic insulators ("capped") of specific creepage 25mm/kV. Bonding of structures with these insulators was often via 1mm² solid copper wires. The copper wire was merely wrapped around the insulator spindles and secured onto the cross arm via washers and nails. This is illustrated in Fig 2 – 6 below. Once again, this application was not as per the requirements of the Engineering Instruction published and hence could be considered as poor bonding. Figure 2 – 7 shows the balance of the bonded cross arm that has burned away. The principle of bonding has again not been implemented correctly.

Figure 2 – 6: Illustration of solid 1mm² copper wire and method used for bonding in Stanger.

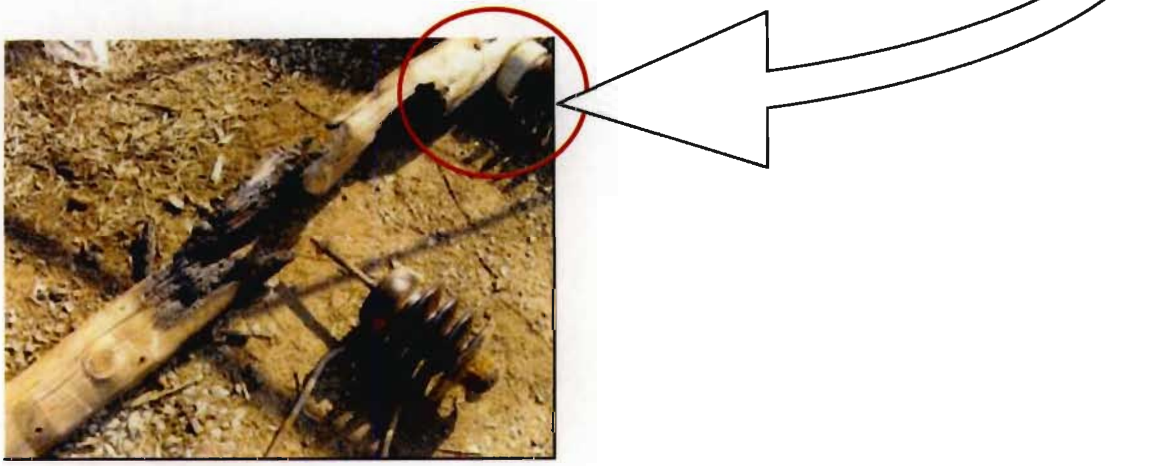


Figure 2 – 7: The balance of the cross arm that is illustrated in Fig 2 – 6 above.

From Fig 2 – 6, there is little evidence of tracking between the ceramic insulator and wood surface. Thus it is speculated that the burning has started from the inside of the cross arm. This is due to a neutral shift which is explained further in Appendix B.

2.2.1.2 Use of Stranded Aluminium Conductor

Further investigations by the researcher revealed the use of stranded aluminium conductor to bond wood cross arms in Mhlatuze just outside of Empangeni on the north coast of KZN. This area is severely affected by cross arm burns. On these structures, the stranded aluminium conductor was merely wrapped around the "dead" ends of the insulator eye – bolts and stapled at various positions onto the cross arm. No real effort was made to ensure proper electrical connections. The pictures below bear testimony to the loose connections and poor application.

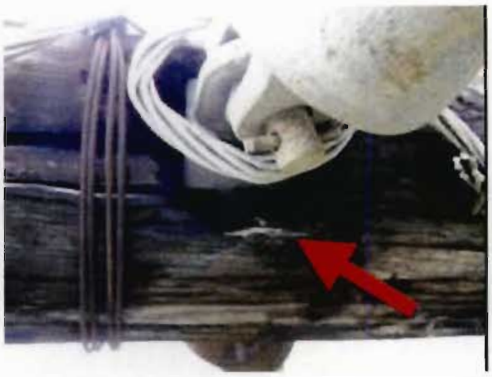


Figure 2 – 8: Poor application of bonding leading to a severely burned hole of eye bolt.

The method applied above did not conform to Engineering Instruction RLC/10. The pictures above clearly show that the principle of bonding was poorly implemented. It is speculated that the leakage current was not properly diverted away from the eye bolt resulting in high leakage current densities to exist at the eye bolt causing it to heat to very high temperatures. With time or age, the cross arm shrinks and allows the wind to penetrate the gap between the eye bolt and cross arm. This air flow combined with the heat of the eye bolt stimulates the burning process.

2.2.1.3 Use of Stranded Copper Conductor

There were many incidents of Pole Top Fires reported in the Mtubatuba area. In 2003 the researcher followed through with one such complaint from the Mtubatuba Technical Service Centre. The complaint was that a bonded cross arm had burned and field personnel were subsequently convinced that bonding of cross arms was not the answer to prevent Pole Top Fires. Investigations by the researcher revealed the use of stranded copper wire to serve as the bonding wire. The application was also wrong as it did not comply with Engineering Instruction RLC/10.

The method consisted of stranded copper wire pressed tightly against the wood cross arm surface via the curved washer and eye – bolt (Fig 2 – 9). The copper wire was also attached to copper bonding clips (Fig 2 – 10) at the steel galvanized threaded rods and merely passed over and adjacent to binding wires as in Fig 2 – 5. This practice led to another problem. Bi – metallic corrosion started to manifest between the copper clips and galvanized threaded rods. This jeopardized the electrical connection and hence the bonding of the structure. This is illustrated in Fig 2 – 10 below. Unfortunately many structures were built with this design. These are some reasons as to why bonded structures continued to burn. The cross arm was severely burned at one end (Fig 1 – 3). Hence this application did not work. This is illustrated below.

Figure 2 – 9: Bonding wire pressed against the cross arm surface.

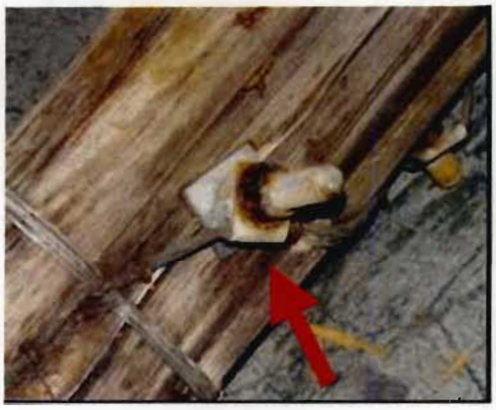


Figure 2 – 10: Galvanic corrosion between dissimilar metals.

Figure 2 – 11: Broken strands of bonding wire.

2.2.1.4 Tracking on a wood pole that is secured to a bonded cross arm with U – bolts

During other investigations in the Empangeni area, the researcher had found scrap samples of burnt poles and cross arms that were returned from the field after breakdowns. These samples were dumped in an area allocated for scrap materials at the Empangeni Technical Service Centre yard.

One interesting sample was a section of a bonded cross arm that was secured to a pole via a steel U – bolt bracket. Pictures of the sample can be seen below. It is shown that the bracket was tightly pressed against the surface of the wood. It was very interesting to find severe tracking at the interface between the U – bolt bracket and a section of the wood pole surface. There were no insulators connected in the immediate vicinity of the pole.

Initially, it was difficult to understand how the leakage current got to the U – bolt bracket and then tracked onto the wood surface. It was speculated that a higher voltage gradient existed on the U – bolt bracket than on the cross arm. The U – bolt bracket has rough edges along its surface. These rough edges create local non – uniform electric fields which causes self sustained electric discharges to take place between the metal surface and wood cross arm surface. Figure 2 – 13 can be electrically modeled as shown in Figure 2 – 12. As can be seen in Figure 2 – 13, the letter A represents the steel U – bolt bracket and the letter B represents the wood cross arm. Steel has a characteristic of very low resistance. That is R_A is very low. Wood has a characteristic of very high resistance. That is R_B is very high. For self sustained electric discharges, a higher induced voltage (V_A) is required on the U – bolt bracket than on the wood surface. From Ohm's Law (V = IR), a higher current (I_A) will flow in the bracket compared to a lower current (I_B) flowing in the wood.

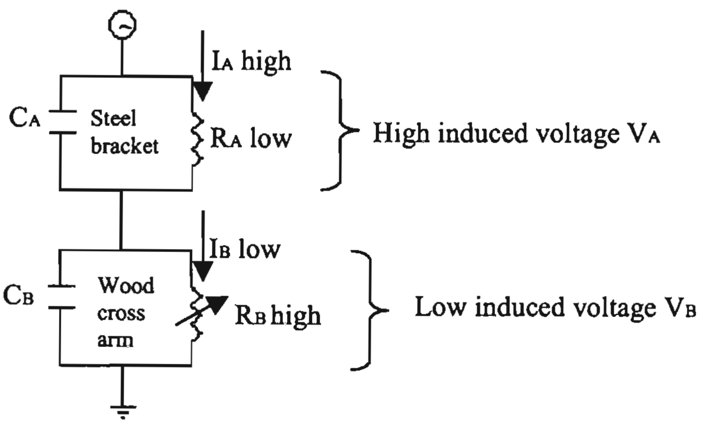


Figure 2 – 12: Electrical model of the steel bracket and wood cross arm (Persadh, 2007).

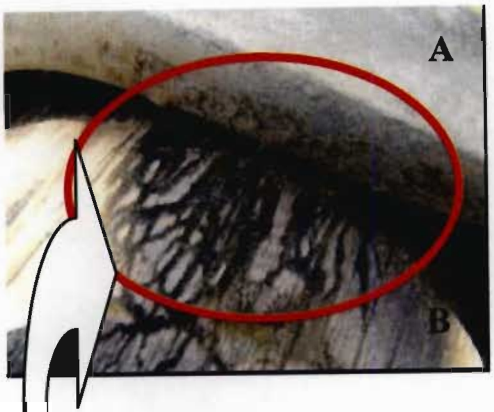


Figure 2 – 13: Severe tracking between bracket (A) and wood pole surface (B).

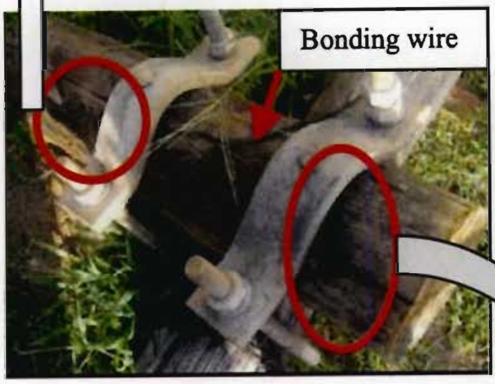


Figure 2 – 14: Cross arm secured via a U – bolt.

Figure 2 – 15: Magnified view of tracking adjacent to the U – bolt bracket

2.2.1.5 Internal burning of cross arms

Amongst the scrap mentioned above, the researcher also found one continuous piece of stranded copper bonding wire that was still attached to the threaded rods and bonding clips. Field staff indicated that this bonding was part of a cross arm where the burning had started from the inside and had completely damaged the cross arm. The bonding installation was still intact. The copper bonding wire was still securely attached to the various threaded rods via clips and washers. The electrical connection was observed to be very good. Sufficient evidence existed to suggest that the burning did start from the inside of the cross arm. The threaded rods were severely burned along its shaft that traverses the cross arm. Once again, this is due to a phenomenon called neutral shift which is explained further in Appendix B. Many such samples were found in that same heap of scrap and some are illustrated below.

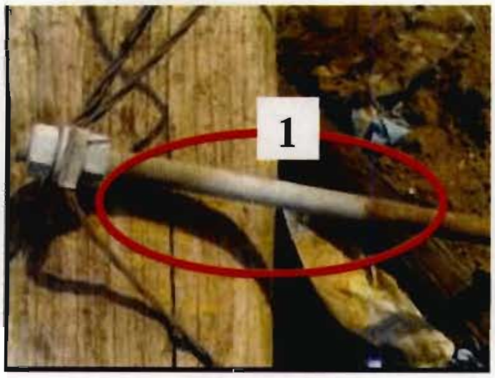


Figure 2 – 16: Burned section of threaded rod number 1.

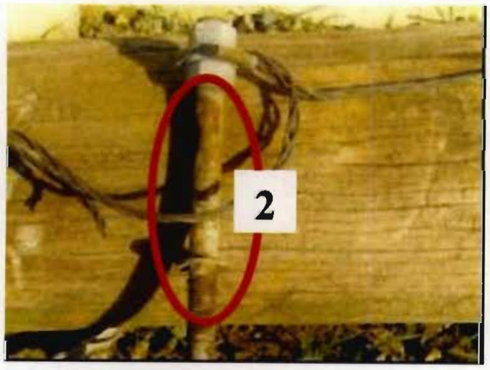


Figure 2 – 17: Burned section of threaded rod number 2.

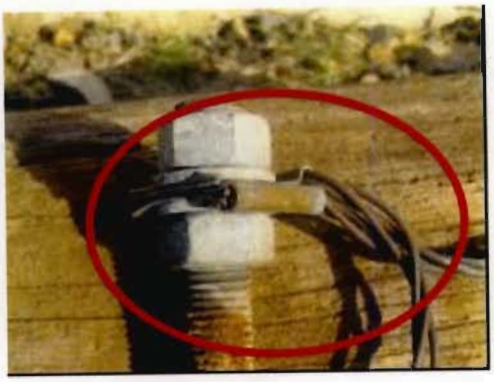


Figure 2 – 18: Good electrical connection maintained between bonding wire, clips, washers and nuts.

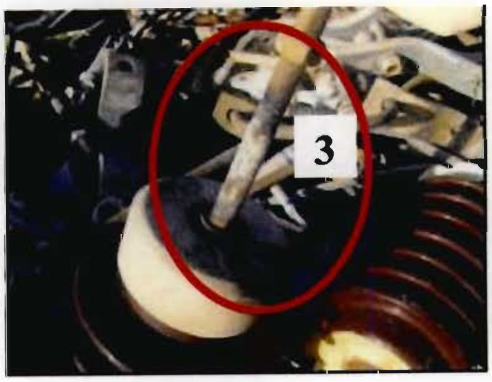


Figure 2 – 19: Burned section of spindle of a "capped" ceramic insulator.

Figure 2 – 20: Severely burned spindle of another ceramic insulator.

The researcher had also found that many of the bonded cross arms that did burn had ceramic insulators of varying specific creepage levels installed. The use of ceramic insulators of different specific creepages has a direct influence on the burning process. The level of pollution on each of these insulators can be variable and thus contribute different leakage currents. As a result the leakage currents on the three phase system do not summate to zero. So there existed poorly bonded and un – balanced systems that contributed to burning.

Thus, from the time that bonding of wood cross arms was introduced, the implementation thereof was poorly managed. Thus far, fires have been experienced on bonded and un – bonded structures with mainly ceramic type insulators of varying specific creepage per structure. The bonding methods illustrated above eventually signaled their flaws as can be seen from above pictures. The choice of materials, design and poor application thereof were some of the reasons thought as to why bonded cross arms continued to burn.

CHAPTER 3: LITERATURE REVIEW

The researcher shall now review literature and studies that have already been undertaken to explain the burning phenomenon.

3.1 The mechanism of burning and the controlling parameters

3.1.1 Mechanism of burning

One of the major causes of pole top fires is air pollution. According to the International Electrotechnical Commission (IEC, 1979), the sequence of events is as follows:
Essentially, the problem is due to a build up of pollution on insulators and wood cross arms. The pollutions contain soluble salts or dilute acids or alkalis. When the pollution is dry, it is non-conductive. However, when lightly wetted by dew or mist, it becomes conductive. Also, if the pollution layer on the insulator and cross arm is deposited as a layer of liquid electrolyte such as salt sprays, then it is already conductive and hence wetting is not a prerequisite (IEC, 1979).

Once the pollution layer becomes conductive, it provides a path for leakage currents to flow from the phase insulators and onto the wood cross arm. The surface leakage currents cause a heating effect which dries out parts of the pollution layer. This gives rise to dry bands on the insulator and wood surface. These dry bands interrupt the flow of leakage current. The dry bands are then bridged by arcs (dry band arcing) which cause a surge of leakage current (IEC, 1979).

Research in the 1940's (Bellaschi, 1947) showed that ignition of the wood is caused by the flow of leakage currents from line fittings, insulators and bolts, into the surrounding wood area. If the magnitude of the leakage current and its density is high enough, ignition of the wood can result.

Laboratory tests have shown the excellent insulation characteristics of wood when dry. It was hypothesized that dry poles were rapidly moistened due to rising humidity, fog, dew or light drizzle. This increases the moisture content on the surface of the pole. However, areas which are under metal fittings are temporarily kept dry. These areas are typically near energized metal fittings and as a result have high voltage gradients (electric fields) across them. This causes local discharges and current activity to penetrate the wood surface, resulting in the surface burning or charring (Hartman, 1994). If these currents are sustained for long periods of time, they could lead to ignition of the pole or cross arm. This effect can be seen in Figures 3 – 3 and 3 – 4 respectively below. The result of further burning can be seen in Figure 3 – 5 below (Persadh, 2003).

The mechanism of burning is further explained in the next section which identifies the controlling parameters for pole top fires.

3.1.2 Controlling parameters

3.1.2.1 Sources of pollution and their significance

Pollution on an insulator or wood pole surface can range from light to medium to heavy, depending on the distance from the coast, prevailing winds, and chemical deposits from local industrial complexes and dust from local agricultural operations (Bradwell, 1983). Pollution typically consists of insoluble oxides, soluble carbonates, nitrates, hydroxides, sulphates and chlorides. The contamination layer can therefore be defined as a mixture between conductive and inert materials. The conductive part consists of ionic salts such as Sodium Chloride, Potassium Chloride and Calcium Nitrate.

The severity of the pollution layer is expressed in terms of equivalent salt deposit density (ESDD) (Van Wyk, 1996). Pollution severity is determined by measuring the ESDD on the surface area of an insulator. ESDD is the equivalent deposit of NaCl in $mgcm^{-2}$ on the surface area of an insulator which will have an electrical conductivity equal to that of the actual deposit dissolved in the same amount of water (Van Wyk, 1996). The relationship between ESDD and site pollution severity is as follows:

Pollution level	ESDD (mg NaCl cm^{-2})
Light	0,03 to 0,06
Medium	0,10 to 0,20
Heavy	0,30 to 0,60
Very Heavy	> 0,80

IEC 60815 Specification shows the relationship between pollution level, ESDD value and the minimum creepage distance (mm/kV) required as follows:

Table 3 – 1: Relationship between pollution level, ESDD value and creepage distance.

Pollution level	**ESDD Value in mg NaCl cm^{-2}**	**Minimum creepage Distance (mm/kV)**
Light	0,03 to 0,06	16
Medium	0,10 to 0,20	20
Heavy	0,30 to 0,60	25
Very Heavy	> 0,80	31

3.1.2.1.1 Veld fires

The hot dry Berg wind conditions that prevail in KZN prior to the pole top fire events are typically severe fire hazard days. Smoke from these fires is transported to the coast via the north-westerly winds that also prevail during these times. Without rain, this smoke remains suspended in the atmosphere and eventually settles on the insulators and wood cross arm surfaces (Diab, 1991).

3.1.2.1.2 Sugar cane burning

Sugar cane is the dominant crop in KwaZulu – Natal. Cane burning is an accepted harvesting technique in KZN and is an alternative to trashing. However, it has a number of negative environmental effects. It is a huge contributor to the air pollution load of the region. It has been estimated that cane fire faults account for up to 30% of all transmission line failures (Naidoo, 1989).

Cane burning normally takes place from late April to the middle of December. This coincides with the dry season. Cane burning is responsible for the emission of sucrose and carbon particles which bond to the insulator surface. This contributes to the slow build up of pollution on the insulators during the dry winter season (Naidoo, 1989).

3.1.2.1.3 Industrial Pollution

Within South Africa and in particular KwaZulu – Natal, major pollution sources exist in the vicinity of Durban and Richards Bay. This area is on the north coast of KZN. The huge industrial growth in the Richards Bay area has resulted in a lot of chemical fumes being released into the atmosphere, thus contributing to industrial pollution. Sulphur dioxide (SO_2) emissions are a major contributor of pollution in this area. The conversion rate of SO_2 to sulphate increases by a factor of 8 as the relative humidity increases from 70% to 80% (Wallace et al, 1977). The high humidities of the coastal environment enhance the conversion and increase the build up of pollution on power lines.

3.1.2.1.4 Dust pollution

Dust particles originate from a variety of sources such as construction activities, agricultural practices and wind blown soil particles. Because of the soil particles small size, they are likely to be transported over vast distances. The north coast of KZN is noted for the above (Diab, 1991).

3.1.2.1.5 Marine pollution

Natural pollutants of salt aerosols sprays are formed over the ocean when water droplets are ejected into the air from breaking waves. The water evaporates leaving behind salt particles which may be transported for considerable distances in the sea breeze circulation, inland (Diab, 1991). The build up of salt is a process that occurs throughout the year and the layer of NaCl on the insulators is likely to act as a base on to which other pollutants settle until the insulator strength is sufficiently reduced to cause pole top fires.

In 1998 Loxton showed winds to be predominantly northerly and south easterly in direction. Northern KZN is directly in line with these prevailing winds which carry contaminants directly from the ocean and industrial areas of Richards Bay. Thus existing pollution in the air could be directed over areas ranging from Stanger in the south to Mtubatuba in the north and also inland to Nongoma where cross – arm burning is experienced each year. These are major driving forces of leakage current activity, resulting in pole top fires (Loxton, 1998).

IEC classifies South Africa as having 75% light to medium pollution and 25% heavy to very heavy pollution (Ellis, 2005). The very heavy pollution areas are highlighted below. The far inland area of Gauteng falls within the area classified as having very heavy pollution. This is mainly due to the huge industrial infrastructure in the area which contributes significantly to pollution. There have been very few incidents of pole top fires in the Gauteng area. The Western Cape is also classified as having very heavy pollution. Feedback from the University of the Western Cape indicates that there have been a few incidents of pole top fires in the Western Cape area (Vosloo, 2006). This then raises the question as to why KZN is more prone to pole top fires, whereas other areas which use the same line design are not. The researcher shall now briefly analyze weather patterns in KZN to attempt to answer the above question.

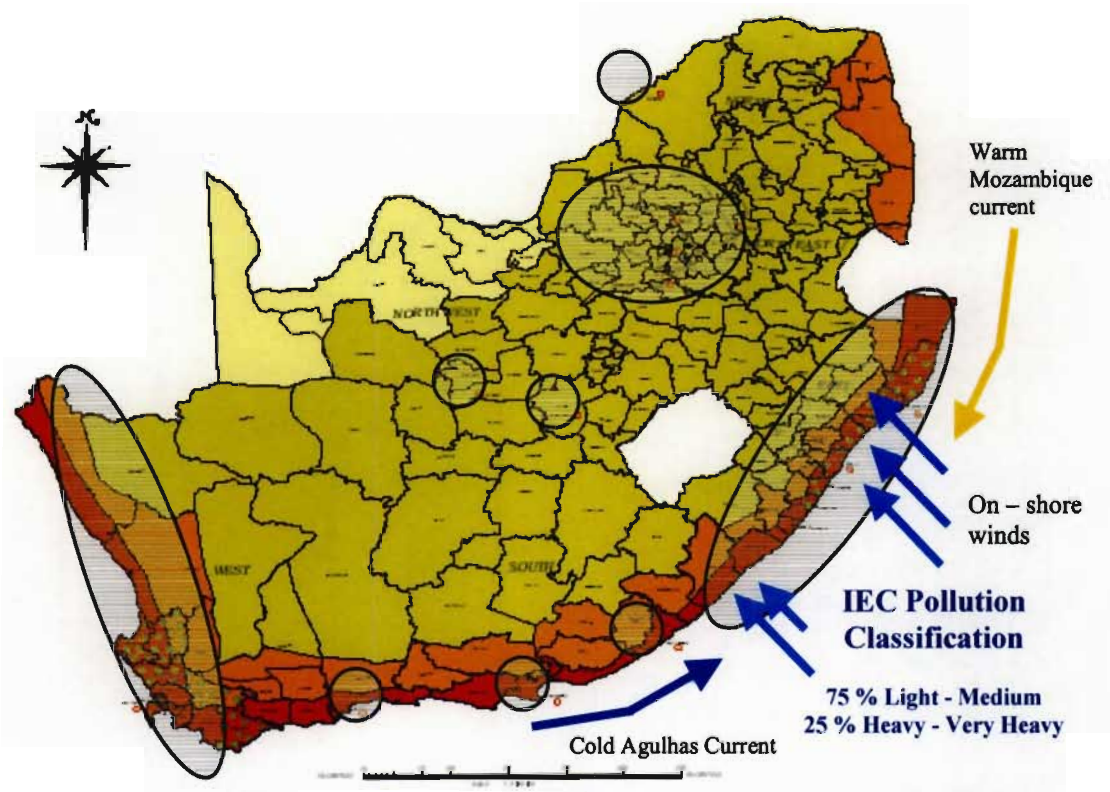


Figure 3 – 1: Pollution map of South Africa indicating shore winds and coastal currents (Ellis, 2005).

3.1.2.2 Weather patterns in KwaZulu – Natal

During the period August to November, the KZN coast experiences a **unique** sequence of weather events that lead to patterns of air pollution potential (APP) (Diab, 1991). Three synoptic regimes exist and each is characterized by distinct APP viz;

a) An established high pressure system: This is characterized by light north – easterly winds and a low mixing depth caused by an upper level subsidence inversion. This is when nocturnal surface inversions develop resulting in poor dispersal capacity of the atmosphere and hence APP is high.

b) Pre – fontal stage: APP increases even further as the subsidence inversion dips towards the surface ahead of the coastal low.

c) Post – frontal stage: This is characterized by strong winds, lifting of the subsidence inversion and often accompanied by rain giving rise to a low APP.

The sequence of changes in the heights of inversions, mixing depths and winds is the characteristic of the movement of coastal lows along the KZN coast. As per Table 2 – 2, most of the pole top fire incidents occur in August. This is at the end of a long dry winter period and of which is characterized by below average rainfall. The presence of elevated inversions is common along the east coast of South Africa. The frequency ranges between 40% in June and 80% in September (Preston –Whyte et al, 1977). Heights of elevated inversions and mixing depths undergo a sequence of changes which are closely linked to the movement of coastal lows and the associated cold front along the Natal coast. The pole top fire incidents in KZN fit neatly into this pattern (Diab, 1991).

The above is now summarized to assist in understanding why KZN is unique to the phenomenon of pole top fires.

Incidents of pole top fires coincide with a period of high air pollution potential. Pre – frontal conditions over KZN are characterized by light winds and well developed mesoscale wind systems which facilitate the recirculation of pollution, low mixing depths and under extreme cases the occurrence of hot and dry offshore Berg winds. All these factors reduce the capacity of the atmosphere to disperse pollution. These conditions coupled with the timing of the phenomenon which is at the end of a long dry winter season during which marine salt and contaminants from sugar cane burning and industrial pollution, settle on the insulator and cross arm surfaces, further increases the potential for pole top fires. Also, the occurrence of runaway veld fires and cane fires immediately prior to the phenomenon result in rapid deposition of contaminants onto the insulators, thus reducing their insulation strength sufficiently to cause high leakage currents (Diab, 1991).

Some of the driving forces along the west coast are (Vosloo, 2006):

- Mainly marine pollution.
- Pollution wind which is driven and directional.
- Fungal growth problems.
- Nearly daily occurrences of marine fog.
- High humidities with directional wetting.

All of the above driving forces contribute directly to the phenomenon of pole top fires. Other areas do not experience these factors as much and hence experience little or no burning of cross arms.

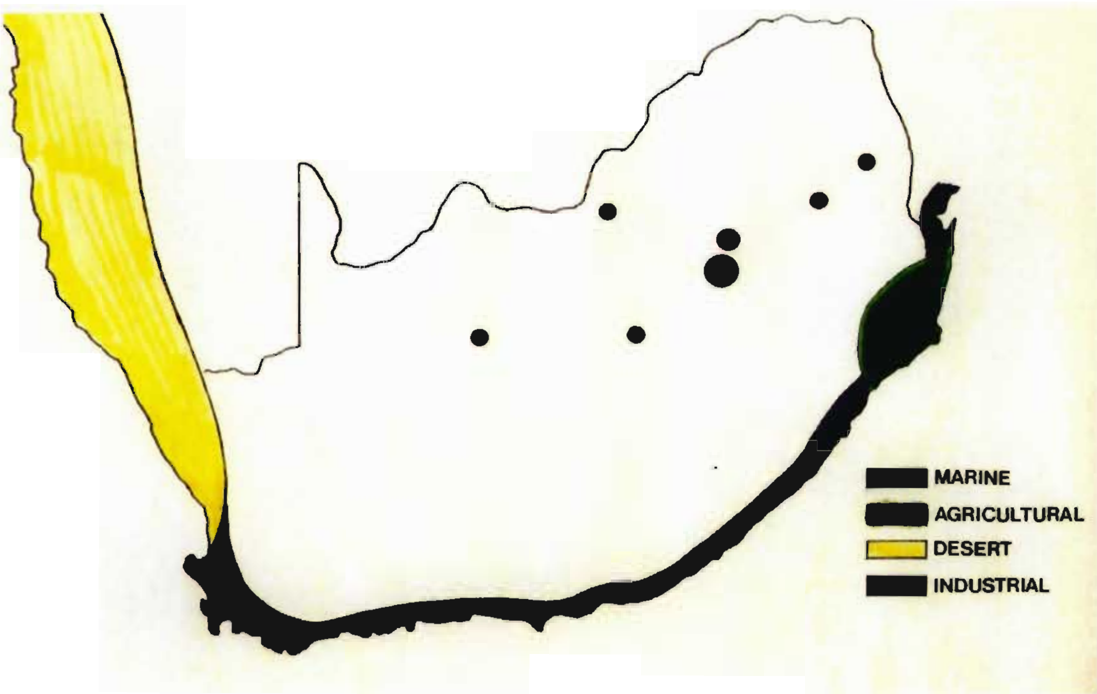


Figure 3 – 2: Pollution type map for SA highlighting coastal pollution (Ellis, 2005).

The subject of pollution is further expanded on in the next section where an investigation was carried out in the mid 1990's to determine leakage current characteristics and the environmental effects of prevailing environmental conditions.

The following pictures were taken on structures in the Mtubatuba area, by the author. The areas highlighted in Figures 3 - 3 and 3 – 4 respectively show signs of early stages of burning. If these are un – detected, they will eventually lead to burns of the extent shown in Figures 3 – 5 and 1 – 3 respectively. These are serious problems as they lead to low hanging conductors of which pose a major safety risk to humans and animals.

Notice that a metal fitting was pressed against the surface of the cross arm.

Figure 3 – 3: Tracking starts on the wood surface from metal fittings.

Figure 3 – 4: Tracking gets more severe and starts to ignite the wood surface.

Figure 3 – 5: The wood surface suffered serious burns. The fire has damaged most of the cross arm.

3.1.2.3 Effects of Leakage Current Activity

In 1997 Loxton showed that leakage current activity depends on the presence of moisture in the air, humidity, temperature and pollution present on the insulator at the time of failure (Loxton A, 1997). Under clean and dry conditions, wood that is in series with porcelain provides exceptional insulation properties (< 410M ohms.m^{-1}). However, once this series combination is lightly wetted and polluted, the high resistance of wood rapidly reduces to less than 100kohms.m^{-1}. Leakage current activity on these polluted insulators is prevalent under high humidity levels. At dusk and the early hours of the morning, humidity and light wetting is common. Hence during these times, surface burning occurs. However, with an increase of ambient temperature following sunrise, temperatures increase rapidly in the KwaZulu – Natal northern region, causing the humidity levels to drop and drying of the wood-pole surface to occur (Loxton A, 1997).

3.1.2.2.1 Investigation determining Leakage Current Characteristics on 22kV Lines

Seasonal burning of wood pole cross arms in the Northern Zululand is a major concern. During June and November of 1995 Loxton carried out investigations to determine leakage current characteristics on 22kV lines and environmental effects of prevailing environmental conditions. He aimed to measure the magnitude of leakage current present between phases on wooden cross arms and show the effect of humidity, temperature and pollution levels on leakage current activity (Loxton, 1995).

The following tests were conducted:

- Measurement of 22kV leakage currents.
- Monitoring of environmental conditions, that is temperature and humidity.
- Determination of the pollution level – ESDD tests.

These tests were carried out in the Mtubatuba area which is north of Richards Bay. Wood pole burning is common in this area between June and November. A 22kV line was used for the experiments. The line was ideally situated away from any forest area and well exposed to the prevailing wind conditions. The investigation was planned over this period to ascertain the effect of the winter period progressing into summer (Loxton, 1995).

a) Measurement of 22kV leakage currents

Leakage current measurements were made directly from the 22kV line. One phase on the cross arm was bonded and the other phase left open to allow leakage current to flow between the phases. The un-bonded side of the cross arm was drilled 300mm from the outer insulator pin to accommodate a dummy pin to be fitted. A current measuring unit was then fitted to the bottom of each pin allowing the current flowing between them to be measured and recorded. The current measurement range was set to measure AC current ranging from 0 – 9mA RMS. This allowed for the low 0 – 1mA area to be recorded with good sensitivity.

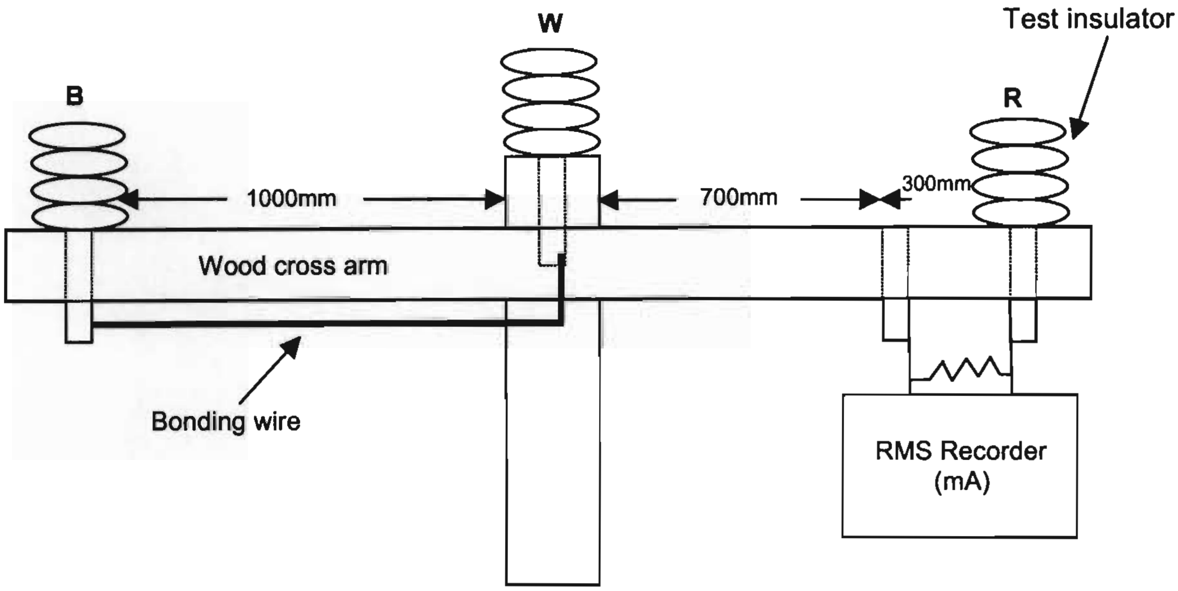


Figure 3 – 6: Diagram of measurement system on wooden cross arm (Loxton, 1995).

The leakage currents that were measured had varying amplitudes. The higher amplitudes were measured at periods of increased pollution which occurred between August and September. These were often at high humidity values. During September, which is a period of high humidity a maximum leakage current of 9.0mA was experienced. The corresponding relative humidity was recorded at 85% and the corresponding ambient temperature was 19.5°C. Many of the recorded currents were found to be of low amplitude (±0.5mA), but of long duration (±3-5hrs) and with sporadic transients of ±3-5mA occurring at various intervals. Appendix C shows the recordings for August 1995. A maximum leakage current of 3.9mA was experienced during this month. However, this tapered to 0.7mA within 45 minutes. The relative humidity was recorded at 99% and corresponding temperature was 18°C.

b) Temperature and humidity monitoring.

These were measured and recorded using data loggers. It was observed that when the humidity was high, there was an increase in leakage current amplitudes. Increased activity was also recorded when the humidity changed suddenly. Ambient temperature was found to have little influence on leakage current activity. However an increase in temperature coupled to a warm inland wind could cause severe resistive and humidity gradients upon the wood pole system when drying and heating of the cross arm occurs, resulting in cross arm fires. Detailed results and graph of the recorded values for the month of August can be found in Appendices D, E and F respectively.

c) Pollution tests

ESDD (Equivalent Salt Deposit Density) tests were carried out to determine the level of pollution in the area. Six insulators of type U70BL were strung beneath the cross arm on the side opposite to the current monitor. An insulator was removed monthly and the ESDD measured.

The Equivalent Salt Deposit Density pollution levels obtained from the suspended insulators were found to be as follows:

Table 3 – 2: Equivalent Salt Deposit Density tests results.

Month	Suspended Solids (mgl^{-1})	Calculated ESDD ($mgcm^{-2}$)
June	8.4	0.0024
July	7.2	0.0020
August	54.2	0.0152
September	131.6	0.0369
October	34.2	0.0096
November	103.2	0.0018

A graph of the results can be found in Appendix G. Although the ESDD measurements indicate a light pollution area high leakage currents were experienced during times of high humidity. When the humidity is high, it results in the light wetting of the light pollution layer which then becomes conductive. It is this conductive layer that promotes the leakage current activity. It is these high and sustained leakage currents that cause burning. Loxton's work is very significant in that the investigations show that, all that is required for wood pole ignition is light pollution and light wetting of which is caused by the high humidity.

3.1.2.4 Influence of insulator specific creepage on leakage current activity

Eskom Field Services staff indicated that wood pole burning occurred over the winter period and prior to the annual rains in northern KwaZulu – Natal (Mathews et al, 1994). This was verified by Loxton's investigations pointed out in the previous section. The high incidents of pole top fires are prevalent over this period due to dry dusty conditions which is aided by dust and salt pollution from the coast. This area has particularly high relative humidity levels (>70%), which allows dampening

of the wood pole structure and insulator surface, thus assisting in contaminating these surfaces (Loxton, 1995).
Insulation level is thus reduced over these periods of high humidity, due to pollutants, such as dust and salt air conditions, resulting in a conductive path causing current flow between phases along the un-bonded wood path. Erratic discharge levels into the wood surface causes burning and tracking from metal fixtures finally resulting in ignition of the wood surface (Loxton, 1996). Evidence of these can be seen in Figures 3 – 3 and 3 – 4 respectively.

Another experiment was conducted by Loxton in 1996 to determine the influence of insulator specific creepage on leakage current activity. This investigation looked at the use of different insulator creepage levels to observe the leakage current activity and amplitude of each insulator respectively. These were the 24mm/kV and 31mm/kV ceramic insulators and specified for a maximum supply (Umax) of 24kV. These insulator types were the Cullinan EP303 (24mm/kV) and a model of higher specific creepage level, EP965 (31mm/kV). The specifications for these insulators appear on Appendices I and K respectively. The measurements were carried out on a 22kV line (Loxton, 1996).

Once again the investigation was carried out in the Matubatuba area. As mentioned in section 3.1.2.2.1 wood pole burning is common in this area between June and November. Hence in order to provide meaningful results, Loxton found it imperative to carry out the investigation during this time and in an area where wood pole burning was prevalent to obtain results which related to the environmental and pollution conditions common to the area.

The measurement was as follows:
Two 22kV wood poles were erected and set up 10 meters apart on a separate test line situated near the Mtubatuba Technical Service Center (TSC). Each cross arm was fitted with a current monitor as illustrated in the pictures below.

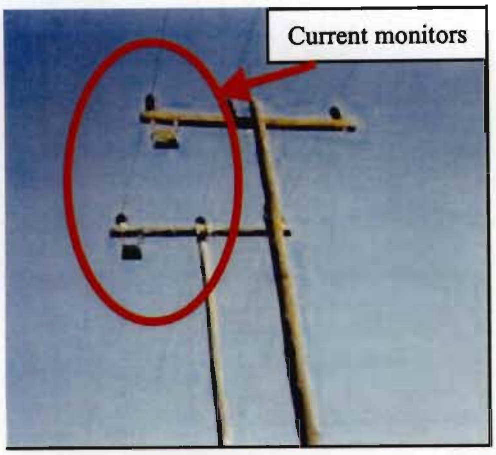


Figure 3 – 7: The test jig erected near Mtubatuba TSC (Loxton, 1996).

One of the wood poles was fitted with a clean set of porcelain insulators of 24mm/kV specific creepage level and the other with a clean set of 31mm/kV creepage insulation level. Figure 3 – 7 refers.

The aim was to investigate the magnitude, duration and frequency of leakage current activity on the two types of insulators. Measurements were carried out between June 1996 and November 1996. Heavy rainfall that started at the end of October 1996 washed the insulators and thus reduced leakage current activity. Measurements for the entire period were recorded and the results appear on Appendix H (Insulator EP303) and Appendix J (Insulator EP965). To make a realistic comparison between the insulators, only leakage current amplitudes of > 1.0mA RMS were extracted from the results and tabulated (Loxton, 1996). Note that sustained currents above 1.0mA have been shown to cause burning.

The claim of 1mA as the threshold is based on earlier research findings which showed that sustained currents of about 1mA flowing into the wood are liable to cause ignition (Loxton, 1994). These results and their respective "Time durations" or period of activity measured was tabulated. A graph of the results was drawn for both insulators in respect of current amplitude, number of events recorded and their associated time durations. These appear in Appendices H and J respectively.

The insulators are referred to as follows: 24mm/kV unit – "Insulator EP303"
31mm/kV unit – "Insulator EP965"

Specifications for the above insulators appear in Appendices I and K respectively. The number of events relating to leakage currents exceeding 1mA RMS and above were recorded as follows:

Insulator EP303	Insulator EP965
69 events	31 events

Time duration of each event number was added to obtain the maximum time of each insulator's activity period over the total number of events taken. These results were as follows:

Insulator EP303	Insulator EP965
310 minutes	86 minutes

From the results it was seen that the 24mm/kV insulator was susceptible to sustained leakage currents of low amplitude (<0.5mA). However, peak currents of 9.0mA RMS were recorded on both insulator types. These peak currents were of extremely short durations of 1 – 1.5 minutes and at different periods. Many of the recorded currents were found to be of low amplitude (±0.5mA) but of long duration (±1 – 10hr) with sporadic transients of ± 2 – 3mA occurring at various intervals. These intervals were less in the case of the 31mm/kV insulator. Graphical comparisons (Appendix H) revealed insulator EP303 as being four times (310 to 86 minutes) more susceptible to leakage current activity in comparison to insulator EP965 (Appendix J). Insulator EP303 showed sustained time durations often in excess of 20 minutes at levels over 1mA. This indicated that the higher specific creepage level suppressed leakage current activity and the lower EP303 (24mm/kV) insulator was inferior in containing leakage current activity.

Furthermore, the EP303 insulator experienced more activity periods in excess of five minutes duration. This indicated reduced insulation levels thus creating a low resistive path which is conducive to increased leakage current activity and longer duration.

The findings and subsequent conclusions of the above investigation are as follows:

- The higher creepage insulator maintained a higher level of insulation. In contrast, the smaller creepage insulator experienced increased levels of leakage activity of 1.8mA. This indicated a possible need for an increased specific creepage level in heavily polluted environments.
- Measurements showed that once environmental pollution on the surface of both insulators had occurred, currents often of similar amplitudes were measured from the EP965 insulator. They occurred much less frequently and were of much lower duration.

- The EP965 insulator is valuable in reducing leakage current activity and durations on 22kV wood pole lines. It was recommended that the EP965 insulator be used in areas of KwaZulu – Natal where wood pole fires were prevalent to improve the integrity of specific creepage insulator levels.
- It was concluded that the EP965 insulator (31mm/kV creepage) could not be used as an alternative option to bonding. There is no guarantee that there will be seasonal rainfall as dry periods do occur during spring and summer. No rainfall will mean that the pollution on the EP965 insulators will not be washed away and hence the same results will not be produced. That is, leakage currents will not be reduced. Without bonding, these leakage currents will accelerate burning of cross arms. However, these insulators could be used in conjunction with bonding in areas where the bonding is considered to be of an inferior nature, thus enhancing the specific insulator creepage levels.

3.2 Field investigations beyond KwaZulu – Natal

3.2.1 Experiences in Kenya

Since the early 1990's, various minor investigations have been conducted in the northern parts of KwaZulu – Natal and reports produced. Many of the reports concluded that cross arms that had burned were either due to no bonding being applied on the said cross arms or that bonding was poorly applied on the said cross arms (Loxton et al, 1996).

During May 1995, Eskom Engineers and the Kenya Power and Light Company (KPLC) inspected parts of the Mombassa – Malindi 33kV coastal distribution wood pole line. Many parts of the network near Mambrui had experienced burning of wood cross arms (Britten, 1995). An idea was to compare the KPLC's problems with those experienced by Eskom in KwaZulu – Natal. Another aim was to deduce the appropriateness of the solutions used in the two organizations. Background details of the burning problem are summarized below (Britten, 1995).

- The 33kV scheme was in service for approximately 15 years.
- The line comprised of unshielded wood pole structures with horizontal wood cross arms. The poles were of Eucalyptus Saligna type.
- The line was mainly parallel to the coast, about 1 to 3km inland on average and approximately 85km long.

- The area is of low isokeraunic level, namely, about 10 to 20 thunderstorm days per year.
- The structures on which burning had occurred were initially fully insulated. That is, the cross arms were un – bonded and the insulation below the attachment point of the two braces was provided by the unearthed wood path of the main pole itself.
- Most of the burning incidents had occurred on the wood cross arms and seldom on the main pole. Furthermore, burning had occurred mainly on the outer phases, at the point where the insulator spindle, washer and nut make contact with the wood surface.
- The KPLC staff attributed the cause of the burning to pollution related leakage currents flowing along the insulator surface and thereafter into the inter-phase wood path of the un-bonded cross arm.
- The line was supplied at 33kV by a solidly grounded star connected transformer (assumed to be 10MVA) (Britten, 1995).

The methods used by the KPLC to reduce or eliminate the burning were as follows:

- The replacement of the 33kV porcelain pin – type insulators (of specific creepage 17 to 22mm/kV) by porcelain line post insulators (of specific creepage 25mm/kV). The un – bonded wood cross arms and fully insulated structures were retained after this modification.
- In areas of chronic burning, such as at Mambrui, wood cross arms were replaced with steel cross arms which were also fitted with line post insulators (Britten, 1995).

It was reported that the above two changes almost completely eliminated the burning problem. Britten offered the following comments on the corrective action taken by the KPLC:

- The mitigation measures taken were technically valid and appropriate.
- The use of steel cross arms instead of un–bonded cross arms is good engineering practice and technically valid as it will almost entirely eliminate burning. However, Britten identified a small risk that burning could still occur at the interface between the bracing straps and wood pole.

The reasons for the small risk of burning are as follows:

For burning to occur at the interface between wood and steel, unbalanced pollution related currents must flow, as shown in Figure 3 – 8. The unbalanced resistive load due to the pollution layer causes the potential of the steel cross arm to rise with respect to the local pole "earth". The pole itself has a finite resistance to true earth, and hence forms the earth of the supply system. In extreme pollution conditions this may cause the cross arm potential to reach the full line–to–ground voltage for short periods, probably for seconds at a time.

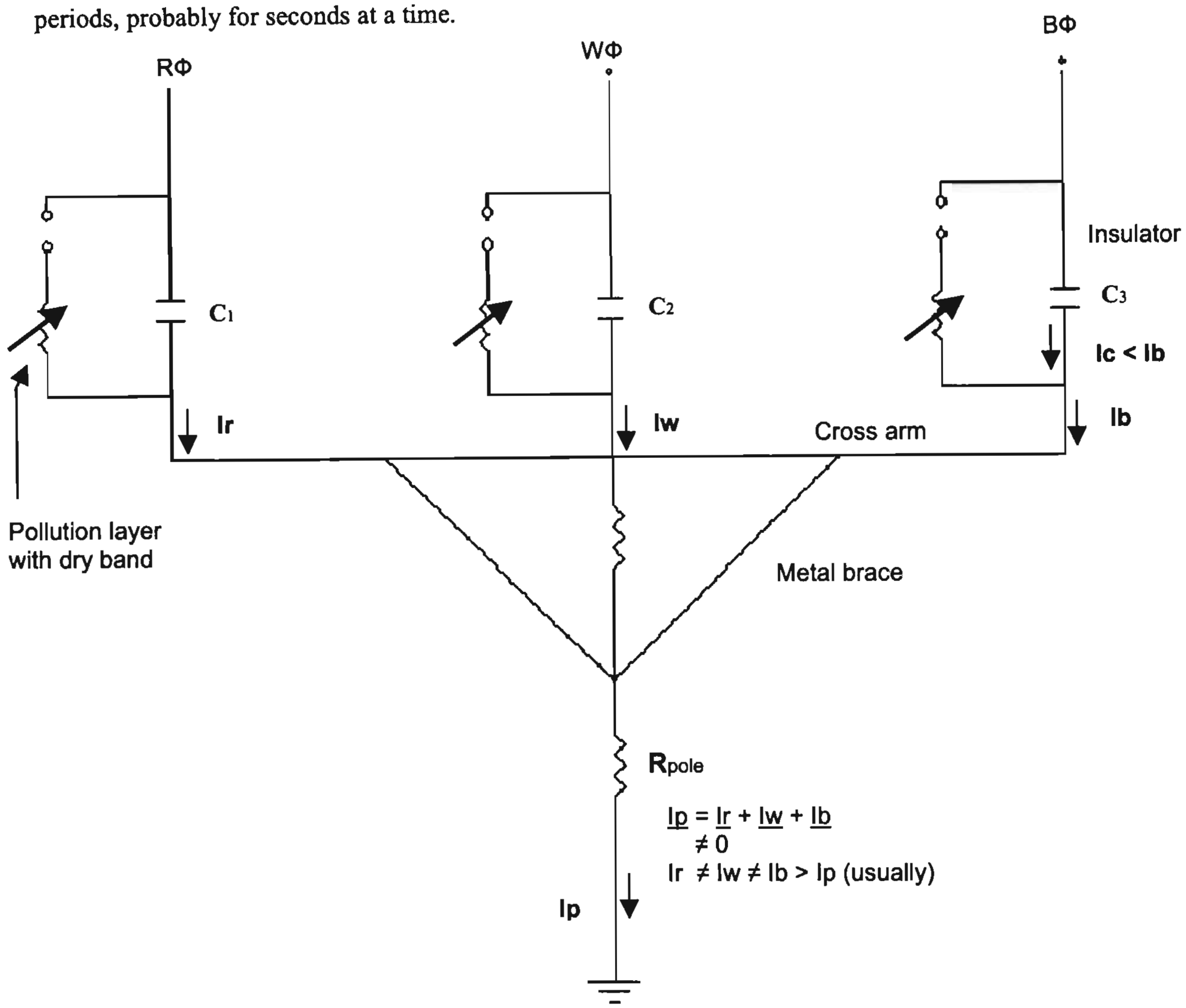


Figure 3 – 8: Electrical model of a steel cross arm. Pollution related currents on a horizontal configuration and vertical wood pole structure (Britten, 1995).

Although there is a small risk of this mechanism causing ignition, it is lower than that associated with wood cross arm burning. The reasons for the lower risk of burning are as follows:

a) Sustained unbalanced impedances would have to exist for several minutes at least for ignition to occur. Britten's experience indicated that this will be a rare event compared to cross arm burning. An earth return leakage current of the order of 1mA RMS means that the insulator leakage currents will usually be higher than a few milliamperes. This will be caused by moderate to severe pollution, as opposed to light pollution conditions. Thus cross arm burning occurs more often than pole burning because:

- Milliampere – level phase – to – cross arm pollution currents will flow whether there are unbalanced impedances or not.
- Currents of such levels can occur in light pollution conditions.

b) With regards to the well aged KPLC poles, it was likely that the resistance of the pole itself was as high as several tens of MΩ. If values of approximately 20 to 50 MΩ are assumed, then the corresponding earth return currents, for light pollution, would range from about 0.97mA down to 0.38mA and probably lower. The higher current could cause ignition, but it would have to be of long duration.

c) The use of line post insulators with the relatively high specific creepage of 25mm/kV tends to keep phase – to – cross arm leakage currents lower than was previously the case with the pin insulators used by KPLC.

d) As far as Britten was informed, there was no evidence of burning occurring at the bracing interface with the pole in the Malindi and Mambrui areas. Similar burning at this point on Eskom's 22kV wood poles is rare compared with the incidence of cross arm burning.

In view of the above, Britten felt that the KPLC should tolerate the low risk of burning at this position on steel cross arm structures and that no protective measures needed to be applied retrospectively. However, on future installations, Britten advised to wrap a metal band around the pole at the point of attachment of the two bracing straps. This was to ensure that the brace-to-wood pole current density remains uniformly low. Conductive paint could also be used instead of banding to achieve the same effect (Britten, 1995).

The significance of the above field investigation was the role of a high insulator specific creepage in helping to reduce the magnitude of pollution leakage currents. At the time of the investigation, the specific creepage of many porcelain line post insulators used in KwaZulu – Natal lines was about 19 to 20mm/kV (Britten, 1995). This creepage was too low. Following the investigation, the Eskom Distribution Insulator Specification was modified to require the use of a specific creepage of 31mm/kV where severe pollution was experienced and caused pole top fires. The use of the steel cross arms should have also been considered as an alternative at the time.

Darveniza has shown that the following essential conditions are necessary for the ignition of wood cross arms and poles by electric currents (Darveniza, 1980):

a) Sustained leakage currents of the order of a few milliamperes (rms) or more must flow from the insulator surface into the wood. As illustrated in section 3.1.2.3, actual cross arm leakage currents in the order of a few milliamperes can last for tens of minutes.

b) High current densities must exist at the points of contact between the metal fittings and the wood surface. This occurs when the insulator spindle fits loosely in the spindle hole, thus creating poor electrical contact with the wood. A further example is sparking between the spindle washer and the wood. The sparking is caused by the presence of a zone of dry high resistance wood (for example, on the weather protected underside of the cross arm adjacent to the washer) which in turn causes a high voltage gradient across this region. If the voltage gradient across the dry zone is high enough to cause sparking, high current densities at the point of entry of the spark into the wood will usually occur. This is assuming poor or no electrical contact between the spindle and the hole that is drilled through the cross arm.

c) Local air movement, such as a slight wind to provide additional oxygen to initiate and sustain ignition.

The overriding and necessary condition is the existence of milliampere – level leakage currents. Such currents can only flow on medium voltage structures if the insulators become coated with conductive pollution. Under clean and dry conditions, the quiescent capacitive currents are much lower and do not cause ignition.

3.3 Laboratory studies

In 1996 studies were carried out at the then Technology Services International (TSI) (Loxton et al, 1996).

Investigations had covered the following areas:

- Resistance measurements on a cross arm that had suffered a burn off.
- The effect of a maintained dry band in the centre of the cross arm.
- Artificial pollution tests on wood cross arm.
- Silicone coated porcelain line post insulator EP303 insulator measurements.
- Cross arm voltage gradient measurements.
- Future preventative methods of controlling leakage currents.

3.3.1 Cross arm wood series resistance measurements

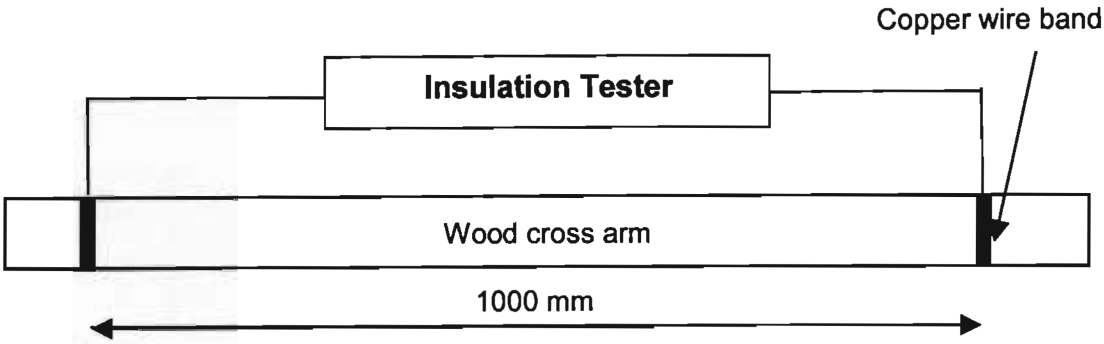


Figure 3 – 9: Diagram to determine the resistance of a cross arm (Loxton, 1996).

In this experiment, a eucalyptus cross arm which had suffered a burn – off was retrieved from site and left in the laboratory to completely dry out at a controlled temperature of 23°C and a humidity of 50%. Copper wire was fixed into grooves which were filed 1000mm apart into the surface of the cross arm. The resistance of the wood was measured across this length under its normal dry condition and under different levels of wetting. This was to determine the effect of moisture on the wood surface. The cross arm was subjected to wetting with distilled water (Loxton et al, 1996). The following results were recorded:

Table 3 – 3: Results of Resistance measurement.

Measurement conditions	Measured Resistance (Ω)
Completely dry pole	410 M
Lightly Wetted	11 M
Medium Wetted	650k
Heavily Wetted	101k

From the above results, it can be seen that wood is an excellent insulation material when dry. The results also show a rapid decrease in resistance when the surface is lightly wetted. This illustrates the effect of sudden light drizzle in the field, after which cross arm burning often occurs (Loxton et al, 1996). Note that these results refer only to the surface resistance and not the internal resistance of which an insulator spindle might see.

3.3.2 Cross arm maintained series impedance investigation

Further tests were carried out on the above cross arm to determine the effect of a maintained dry band in the centre of the cross arm. A maintained dry band will maintain a continuous high resistance under all weather conditions (Loxton et al, 1996). The aim was to prevent leakage currents from occurring in or around the insulator area.

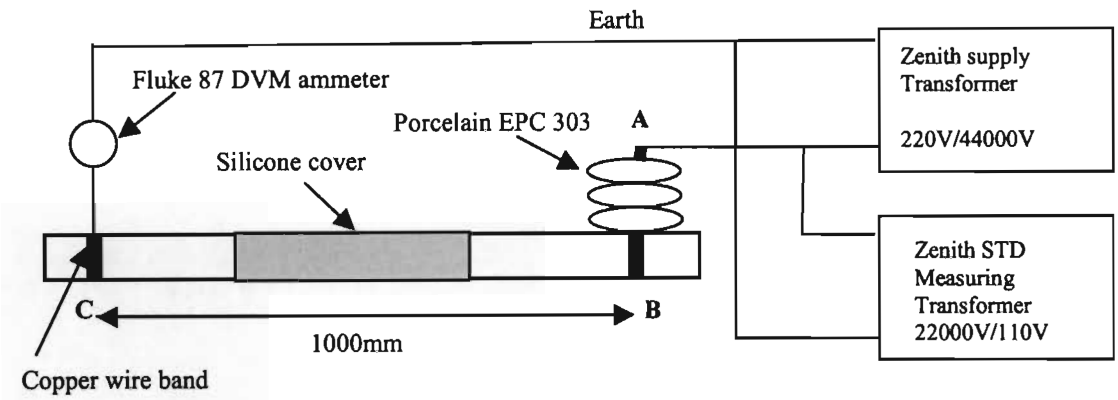


Figure 3 – 10: Laboratory measurement of leakage current on a cross arm with maintained series resistance using a Silicone cover. (Specific creepage of the insulator = 24mm/kV) (Loxton, 1996).

The method of measuring the leakage current was as follows (Loxton et al, 1996):

- Silicone sheets of 500mm, 300mm and 100mm were cut and applied to the centre of the cross arm for each test to maintain a dry band of high resistance. The use of silicone was to maintain good hydrophobic properties and subsequently maintain a high creepage level across the surface of the wood under high levels of pollution. The silicone sheet was wrapped around the centre of the cross arm and secured at each end with a piece of copper wire.
- Distilled water was lightly sprayed over the whole surface of the cross arm and insulator to wet the surfaces to initiate current activity.
- The insulator had been polluted with a medium pollution level mixture of Kaolin and Sodium Chloride.
- The leakage current was recorded as the voltage was increased to approximately 12.5kV. This was carried out for each silicone sheet that was applied to the cross arm, starting with the 500mm sheet.

The results were as follows:

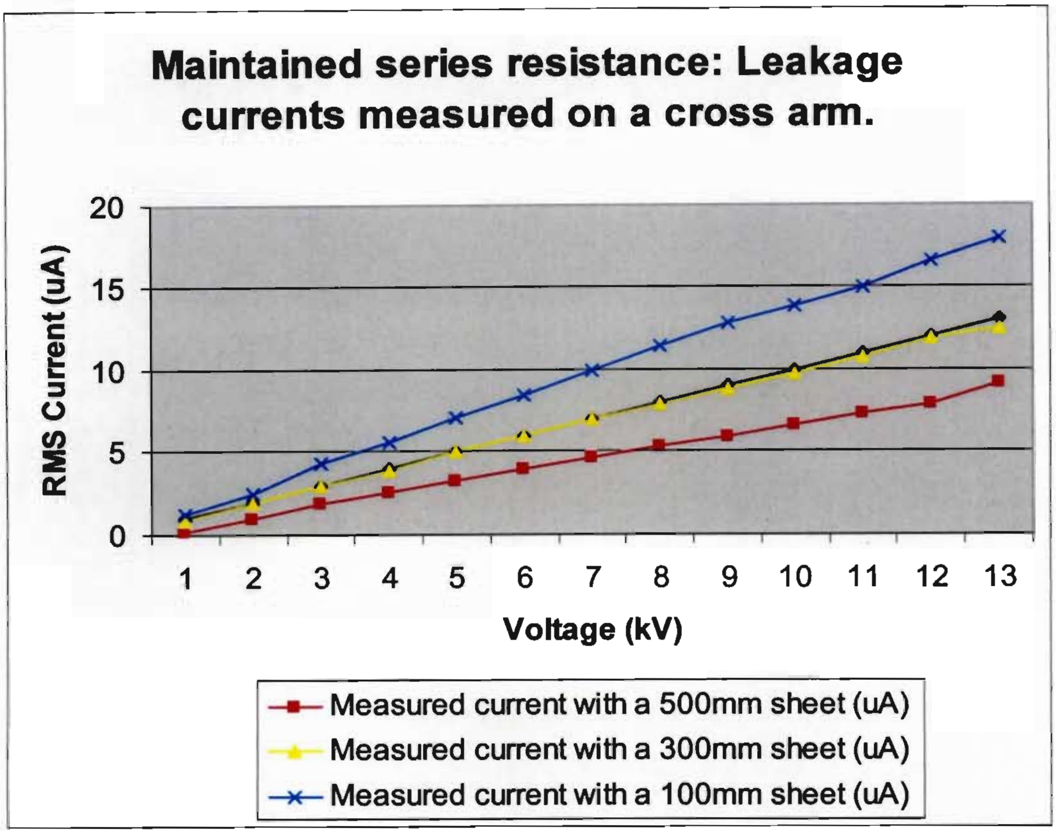


Figure 3 – 11: Maintained series resistance on a cross arm – leakage current results (Loxton, 1996).

From the graph, it can be seen that the leakage current is limited to a very low level. Also, the results show that the current activity is controlled by the length of the series resistance imposed on the series circuit, that is the longer the silicone sheet, the lower will be the leakage current (Loxton et al, 1996). The cross arm surface was kept dry maintaining a high wood path resistance, thus preventing a path for leakage currents to occur.

3.3.3 Artificial pollution tests on wood cross arms.

Further laboratory tests were conducted at the then Technology Services International (TSI) by Loxton to investigate artificially imposed pollution on a cross arm that was again taken from the field in KwaZulu – Natal. The cross arm was allowed to dry in a controlled environment of ±25°C and 30% humidity.

High voltage tests were carried out using the standard test transformers available in the laboratory. The Zenith supply transformer of ratio 220V/44000V and rated at 3kVA was monitored using a Zenith standard measuring transformer set on a ratio of 22kV/110V. Since the operating voltage of the 22kV line is 22kV / √3, the primary voltage output was varied from 0 – 12kV RMS (Loxton et al, 1996).

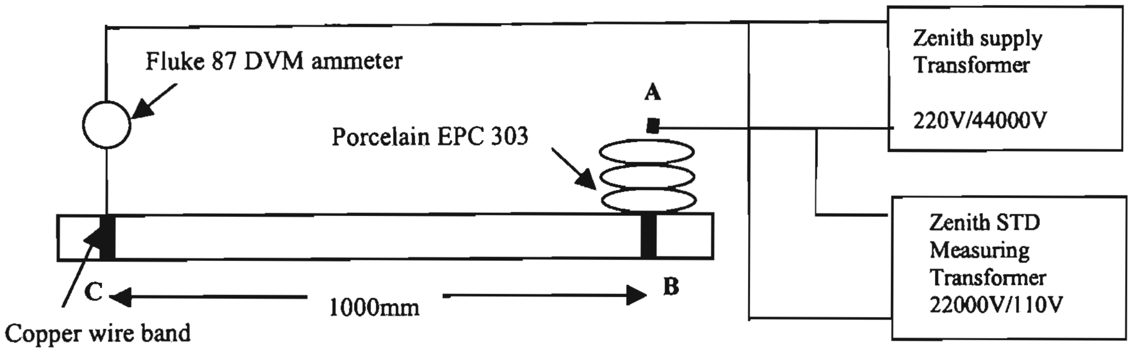


Figure 3 – 12: Laboratory test set up for artificial pollution tests on wood cross arms (Loxton, 1996).

The test required a completely dried out cross arm. This was necessary to simulate long dry winter conditions and be wetted through varying tests relating to site conditions. The resistance of the cross arm was measured to be in excess of 40 megohms. The cross arm was wetted using a fine spray mist bottle containing distilled water. Pollution of the insulator was achieved using a 2% Sodium Chloride solution that was sprayed onto a clean insulator (Loxton et al, 1996).

Tests were also aimed at investigating the area around the base of the insulator under clean and polluted conditions. This area has a direct bearing on the ignition mechanism and leakage current activity. The following tests were carried out:

- To verify current flow with the system clean and dry.
- To determine if any current flow is present when the insulator and entire cross arm is wetted.
- To determine if leakage current activity exists only when the insulator is polluted and the cross arm is dry.
- To determine what current activity is present when the insulator is polluted and the cross arm is lightly wetted.
- To determine what activity is present when the insulator is heavily wetted with pollutant and the cross arm is wet.
- To determine if leakage current activity is confined only to the base of the insulator.

The results of the above tests were as follows:

- Under clean and dry conditions, a maximum current of 4.4uA was measured in the circuit.
- The cross arm was kept dry and the insulator wetted with distilled water. This revealed an extremely low leakage current of 11.8uA, indicating that ideal insulation conditions exist.
- When the whole circuit was wetted with distilled water, it showed a small increase in current activity to 41.4uA.

Hence, under clean conditions, leakage current activity is less than 80uA (RMS). Pollution however has the following effects:

- The cross arm was maintained at a dry level and the insulator was lightly polluted. The wood path impedance maintained a high insulation factor thus limiting the current to a maximum of 21.3uA only. Thus the lightly polluted insulator has a low effect on the circuit (Loxton et al, 1996).
- The cross arm was moistened by light wetting from the mist spray to simulate a light drizzle. The insulator became polluted with the pollutant and immediately 190uA was experienced at only 1kV. As the voltage was increased to 7kV, the current climbed steadily to 2.2mA at which point smoke started to develop from the base and washer end of the circuit. At 3.5mA and 9kV, the whole insulator was emitting surface sparks and the pollutant started to ignite (Loxton et al, 1996).

The base of the insulator developed sparking which was transferred into the wood by the pollutant dripping into the area. As the pollutant found a pathway into the grain of the wood, it caused the wood to ignite in tiny bursts of energy. Once the pollutant was dried from the heating, the current started to gently subside. A very important question is now addressed. That is, does leakage current amplitude of 1mA (RMS) sustain ignition of the wood cross arm? The current was maintained at 0.8mA to 1.1mA and the lower end of the insulator continued to exude smoke. If it was left on and maintained at this level, the burning inside the area would have kept on burning. This verified that one of the primary requirements of the mechanisms of ignition is moisture. This can be in the form of a mist, a drizzle or elevated humidity %. Coupled to this condition, the pollution level of the insulator played a major role in that the insulator became a resistive device allowing tracking of the line voltage to occur (Loxton et al, 1996). Finally, the cross arm was allowed to dry overnight and again tested to measure the current flowing under dry and wet conditions. The insulator was shorted between points A and B. This reduced the circuit to a purely resistive one between points B and C.

It was seen that under dry conditions, the current increased to a maximum of 8.1uA at 12kV (RMS). Once the wood was wetted with distilled water, the current immediately increased at 1kV (RMS) to 4.3mA, thus showing the direct effect of wetting of a wood structure. Note that this pole was removed from site and may have been impregnated with pollutants such as chlorides. When wet, these produce a conductive path for the current (Loxton et al, 1996).

The following Figure indicates the amplitudes of leakage currents at varying voltages and at various pollution conditions.

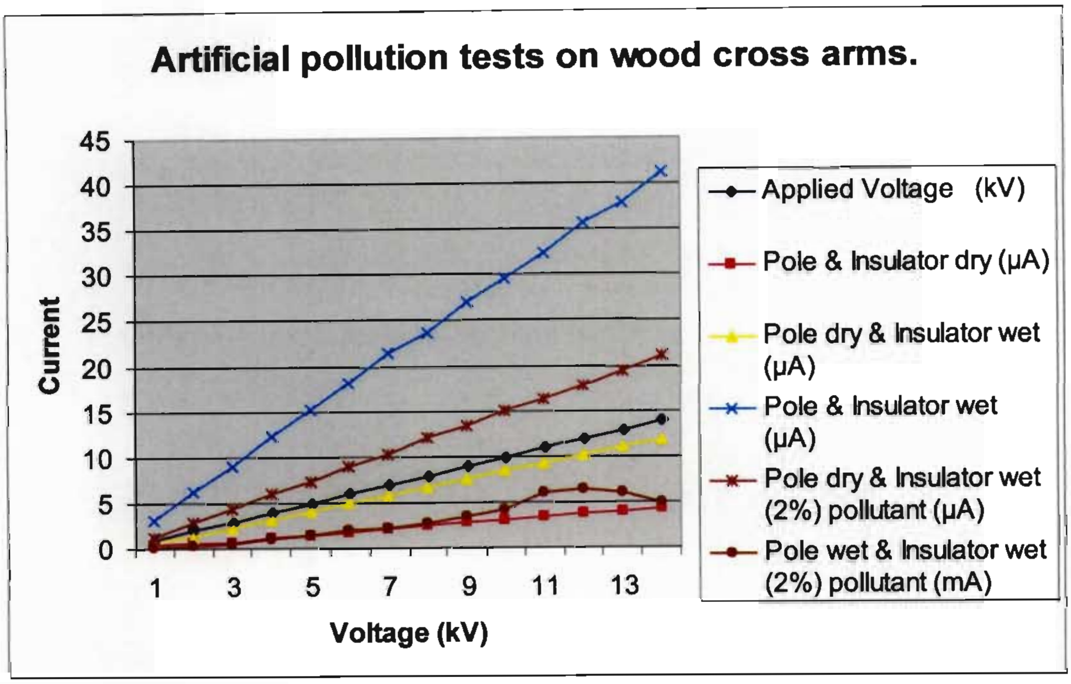


Figure 3 – 13: Results of leakage currents at varying applied voltages and at various pollution conditions (Loxton, 1996).

The conclusions of the above test can be summarized as follows:

A clean dry cross arm and a lightly polluted insulator has a low effect on the circuit. The leakage current activity was kept below the burning threshold of 1mA. The light pollution consisted of a mere 2% solution of Sodium Chloride. When the cross arm was moistened to simulate a light drizzle and with a mere 2% pollution severity on the insulator, a large leakage current of 3.5mA (at 9kV) started to flow causing sparks and ignition of the pollutants. Thus, one can appreciate the magnitude of leakage currents that would flow at 22kV. From this it can be seen that pollution severity becomes significant at a mere 2%. Hence severity of pollution has a major influence in the burning process. Furthermore, once the pollutant was dried from the heat, the current started to slowly subside. However, once the wood surface was wetted again the currents immediately increased to the burning threshold, thus showing the direct effect of wetting.

Hence, one of the main requirements of the mechanisms of burning is moisture which can be in the form of mist, light drizzle or high humidity. Furthermore the pollution level on the insulator provides the resistive device that allows tracking of the line voltage. This then explains why burning of cross arms in the field occur on the onset of light drizzles and during times of heavy mist and high humidity levels. Heavy mist is usually experienced during the early hours of the morning and late evenings.

3.3.4 Silicone coated EP303 porcelain insulator tests

The insulator was coated with silicone and tested to evaluate its specific creepage capabilities in the laboratory after a two year period of climatic and environmental exposure on site. The insulator surface was seen to have surface contaminants and had changed colour slightly to a light grey colour (Loxton et al, 1996). The specification for the EP303 porcelain insulator is given in Appendix I.

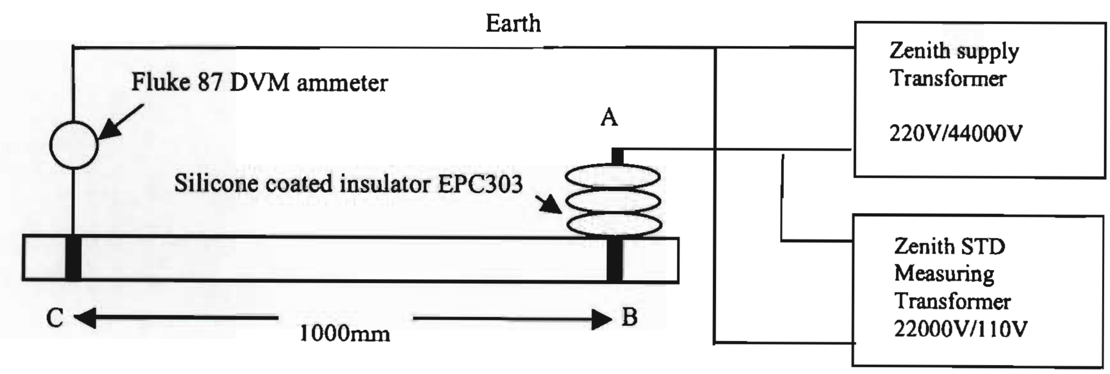


Figure 3 – 14: Laboratory configuration for Silicone Coated EP303 porcelain insulator leakage current tests (Loxton, 1996).

The surface was lightly wetted with distilled water to verify the surface capability with respect to its hydrophobic properties following lengthy environmental exposure. The total insulator surface was then subjected to light wetting including the cross arm surface to evaluate its specific creepage capabilities under normal applied voltage levels of 12.5kV and again at elevated levels of voltage, namely 14kV which is 20% higher than normal operating conditions (Loxton et al, 1996).

The surface of the insulator was then left to dry and then artificially polluted with a medium solution mixture of Sodium Chloride. The total cross arm surface and the insulator was again lightly wetted with the distilled water to see if current of higher magnitude would result when energized to the above levels of voltage.

The result of the test was as follows:
The silicone surface maintained a good level of hydrophobicity with beading immediately taking place. Under both conditions of wetting in the laboratory, the maximum leakage current recorded was 0.1mA RMS even though the surface had been artificially polluted to create a resistive path for leakage currents. The results showed the excellent capabilities of this silicone coating. Silicone has thus far proved its excellent capabilities in maintaining a high resistance path, thus reducing leakage currents. However, it is not practical to coat all existing porcelain insulators in the field with silicone to get the desired effect. It is however, practical to rather use silicone insulators.

3.3.5 Cross arm voltage gradient measurements

The aim of this test was to ascertain the voltage grading along a wood cross arm on an energized structure. The insulator / cross arm combination was configured as shown below. The insulator was artificially polluted using a medium pollution mixture of Sodium Chloride, Kaolin and distilled water. The set was energized to 12.5kV RMS and the voltage measured at each copper strip placed at 200mm intervals with a Sensorlink 8014 fibre optic high voltage probe calibrated in the laboratory. The current was measured on the in line Fluke multi-meter (Loxton et al, 1996).

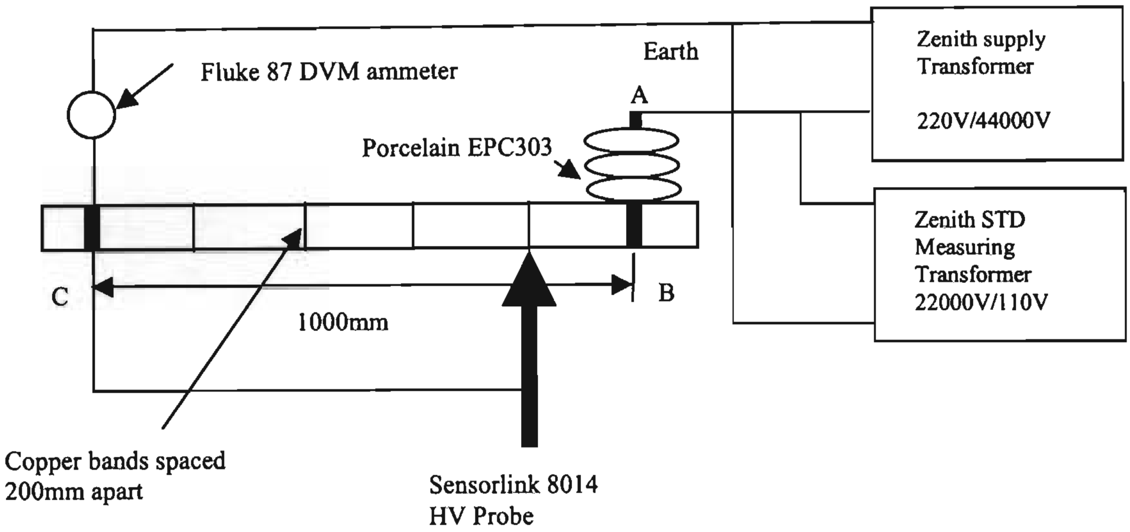


Figure 3 – 15: Laboratory measurement of voltage gradients on a wooden cross arm under polluted conditions using an EP 303 porcelain insulator (Loxton, 1996).

The results were as follows:

Leakage currents in the order of 25mA RMS were measured with a surface voltage of 5.6kV at the 800mm mark measured from point C towards point B, reducing to 1.1kV at the 200mm mark measured from point C. The voltage gradients were seen to be present on the surface of the cross arm and increasing in severity closer to the insulator base area.

Table 3 – 4: Results of measured voltage gradients [distribution] on a wooden cross arm with an artificially polluted EP 303 porcelain insulator.

[------------- Distance from ground (C) towards point B -----------------------]

Applied voltage	200mm	400mm	600mm	800mm
12.5kV	1.1kV	2.4kV	3.8kV	5.6kV

The conclusion from the above test can be summarized as follows. Voltage gradients are present on the surface of wood cross arms of energized structures. The voltage gradient increases closer to the line voltage or base of insulator.

3.3.6 Future preventative methods of controlling leakage currents

A number of alternative solutions to prevent cross arms from burning were investigated (Loxton, 1998). These are briefly described below.

- Maintained series impedance on the cross arm.
- Conductive paint applied to the surface at 100mm on either side of the insulator.
- Banding which involves the application of a copper strip from the insulator pin to a point about 200mm away from the pin and encircling the pole.
- Guarding, which is a short length of copper strip is fixed to the insulator pin and fixed to the cross arm 200mm away.

Each of these methods were set up in the laboratory and tested under clean fog conditions. Measurements were carried out under an applied humidity that was controlled between 50 to 90%. The objective of the tests were to prove their capabilities in being effective in overcoming leakage current activity or in preventing any form of burning or ignition taking place on wood pole surfaces (Loxton, 1998).

3.3.6.1 Maintained series impedance test

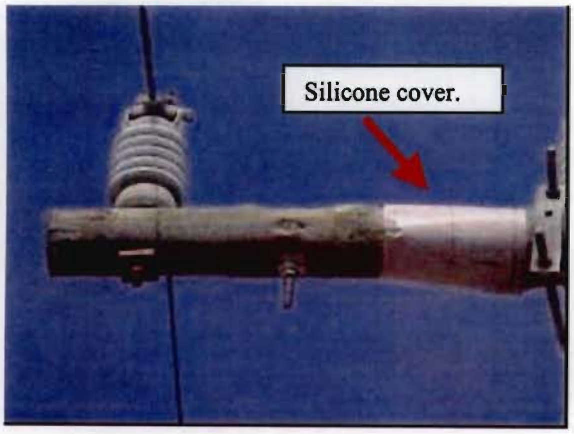


Figure 3 – 16: Illustration of maintained series impedance test showing the 300mm long silicone cover. (Loxton, 1998).

This test was similar to that in section 3.3.2 above. The section of the cross arm surface was kept dry maintaining a high wood path series resistance, thus restricting any leakage current flow that would ignite or burn the wood surface.

3.3.6.2 Conductive paint test

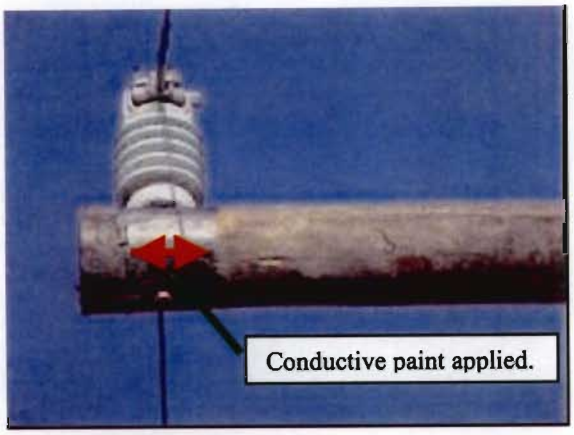


Figure 3 – 17: Illustration of conductive paint applied to the cross arm 100mm on either side of the insulator pin (Loxton, 1998).

The test sample was exposed to the same conditions as in 3.3.6.1 above, except that the insulator was changed to one with a specific creepage level of 24mm/kV. The test sample was energized to 12.5 kV and the current recorded. The results were as follows:
On energizing the sample, the wetted insulator started emitting flashover sparks between the sheds and onto the surface of the conductive paint. The current immediately rose to 32 – 40mA RMS. The unit remained energized for 20 minutes. After the insulator sheds had become dry from the heating activity on the surface, little or no activity was observed. At all times during the test, no traces of surface burning or smoke were seen at all. There was no burning to the cross arm surface at all (Loxton, 1998).

The conductive paint was applied with a paintbrush on the brushed wooden surface. After nine months of being in service, the paint started to flake and crack at various points on the cross arm. This was due to the unstable surface of the wood and the harsh weather conditions causing wetting, heating and cooling of the wood. Although this method showed extremely positive results in overcoming burning, the results were disappointing as the lifespan of the conductive paint had reduced by three quarters. The formula for the conductive paint needs to be further investigated and worked on to cater for the longer durations in the field. It should have a lifespan of at least twenty years. Hence applying conductive paint is an excellent method to overcome pole top fires, however, it is not yet practical as the paint is not yet durable for the long periods required.

3.3.6.3 Banding test

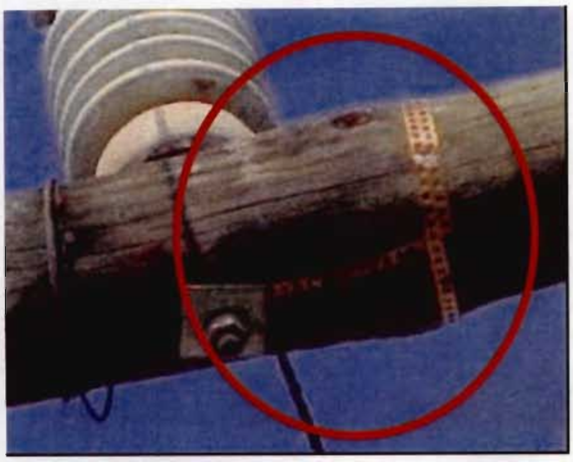
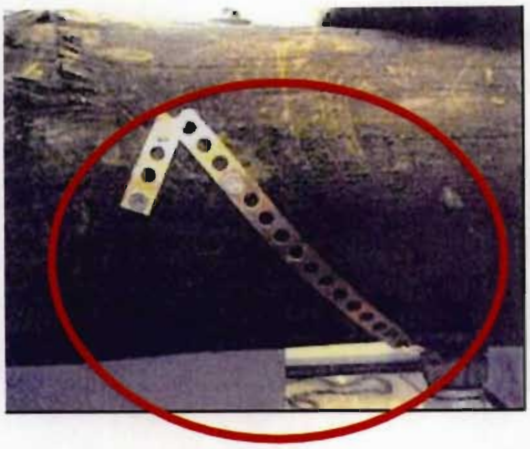


Figure 3 – 18: Illustration of the application of banding to the cross arm (Loxton, 1998).

Banding is a method whereby a copper strip is taken from the bottom of the insulator pin and taken once around the circumference of cross arm. The strip is nailed into the cross arm to maintain a good connection (Loxton, 1998). The copper strip allows any leakage current to be diverted away from the insulator area into the resistive area of the cross arm. The test was carried out on in a fog chamber with the relative humidity controlled to 80%. The test sample was allowed to soak for 30 minutes prior to being energized to 12.5kV RMS and the current recorded. The results indicated that the current immediately rose to 31 – 35mA RMS and subsided to 1.2mA after 5 minutes. Also, throughout the duration of this activity, sparking was observed between the sheds of the insulator but no visible surface burning was seen. No smoke was observed at all (Loxton, 1998). The method was successful in preventing burning from taking place however; there is no evidence of what is happening inside of the wood where the spindle is in contact with the wood. Further investigations need to be conducted to ascertain what happens between the spindle and wood.

3.3.6.4 Guarding test



Figures 3 – 19: Illustration of copper strip attached to the bottom of the insulator pin and fixed approximately 200mm from the insulator pin (Loxton, 1998).

The copper strip was bolted to the bottom of the insulator pin and taken towards the centre of the cross arm. This removed the leakage current concentration away from the insulator pin thus preventing any form of ignition or surface burning. The test sample was set up the same as in the maintained series impedance test described in 3.3.6.1 above and the same environmental conditions were adhered to. The result was similar to that of the banding experiment above. On energizing the test, the current immediately rose to 21mA and slowly subsided after 7 minutes to 1.3mA as the pollutant dried on the surface of the insulator. No ignition or burning was observed (Loxton, 1998).

Due to ease of application and efficiency in preventing burn offs on un – bonded cross arms, this method was suggested for implementation in the field. The important feature with this method is that it maintains the series wood path impedance required under high lightning conditions.

3.3.6.5 Conclusions from the above tests

- Although the results of all of the above tests proved to be successful in preventing pole top fires, not all are practical. The proposed methods need to be applied easily with long lasting capabilities (Loxton, 1998).
- The method of guarding was seen to prevent burning even under high levels of leakage current activity on the wood surface under wetted conditions. It was also considered an alternative to bonding in areas where high lightning activity is present. This is due to maintaining the high

wood path series resistance (Loxton, 1998). However, the activity between the insulator spindle and inside of the wood cross arm needs to be further investigated.

- The silicone coated porcelain insulators reduced the leakage currents considerably (Loxton, 1998). However, due to the current skills shortages it is not practical to coat all existing porcelain insulators in the field with silicone to get the desired effect. It is however, practical to rather use silicone insulators.

3.4 Insulation co – ordination

Insulation co – ordination is achieved when the insulation strengths of all components of the electricity system are adequate to withstand the electrical stresses of service within selected reliability margins (Crowdy, 1999). In Eskom Distribution's medium voltage (11kV and 22kV) networks, the insulation co-ordination is designed to ensure the lowest probability of power outages and failures for the capital spent. The selection of the bonding and basic insulation level (B.I.L) rating for a line is dependent on the lightning activity in the area and the pollution levels (Crowdy, 1999).

For medium voltage wood pole lines, the Eskom Distribution standard arrangement is that all the spindles of all phases are bonded and an earth wire is installed down along the pole. A gap of 500mm is left between the bonding wire and the earth wire. A circumferential strap is utilized on either side of the gap and connected to the earth wire and bonding wire respectively (Stanford, 2004). The arrangement is to provide the following:

- An alternative path for the leakage current, hence preventing concentrated leakage current activity at the insulator spindles that eventually cause burning.
- 300kV insulation level between the phase conductors and ground.
- Reduced probability of wood pole top burning and pole degradation resulting in reduced operational cost and improved safe conditions.

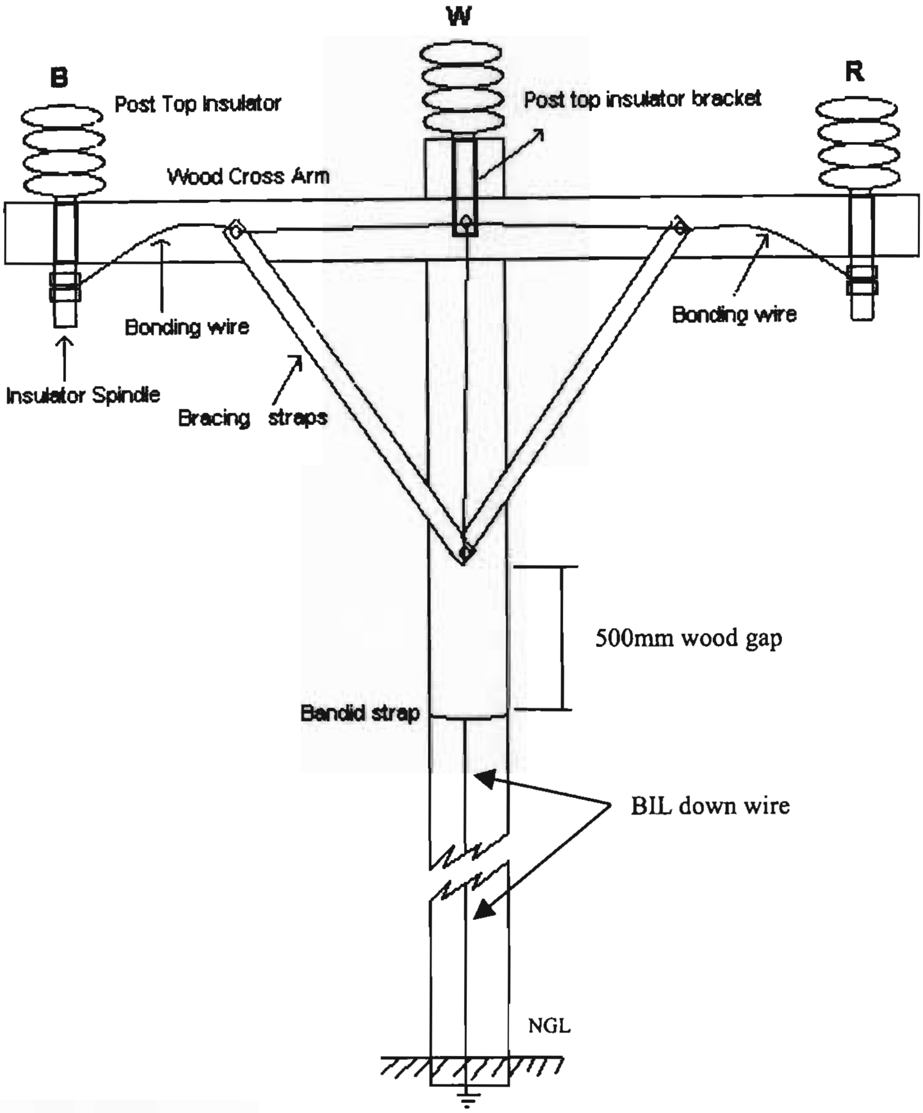


Figure 3 – 20: Diagram illustrating insulation co – ordination (03TB - 034).

The type and extent of lightning damage that occurs on pole and cross arms depend on factors such as the moisture content and the lightning penetration into the wood (Stanford, 2004). Wood poles and cross arms suffer the least damage when the lightning arc can be restricted to the surface of the wood where superficial splintering may occur. This is achieved by having a minimum wood path gap in the earth wire of 500mm and applying circumferential strapping at termination points of the BIL down wire and bonding wire on either side of the gap. The circumferential strapping prevents the arc from penetrating the wood pole to bolts (Crowdy, 1999).

One of the main findings from research carried out by the CSIR and Eskom is that on an unshielded wood pole structure 8m high, the probability of an induced surge exceeding 200kV is far lower than the probability of a direct strike to the line. For this reason, and to allow for tolerance for wet insulation performance, a basic insulation level of about 300kV on each structure will minimize the outages caused by induces surges (Erikson, 1986).

3.5 Bonding of line hardware

3.5.1 Bonding of Wood Pole Structures

Based on the literature studies above, research demonstrates that due to various factors such as pollution, moisture content or humidity, wind and sustained leakage currents, un – bonded cross arms can eventually burn. Research has also demonstrated that the bonding on wood pole structures reduces burning. The principle of bonding discussed below must be read in conjunction with the Engineering Instruction RLC/10 and drawing DEN 900904 in Appendix A.

3.5.2 Principle of Bonding

The principle of bonding is that all the metal hardware and insulator "dead" end fittings on a wood pole structure shall be effectively and electrically connected together. The bonding wire provides an alternative circuit for the high density leakage current to flow away from the base of the insulator and wood surface of the cross arm. The principle of bonding was thought to have the following effect. That is, with the leakage current flowing away from the wood surface, there is little chance of burning occurring. The principle of bonding is illustrated in the following figure. The bonding connections are as per drawing D-EN-900904 in Engineering Instruction (RLC/10) that appears in Appendix A.

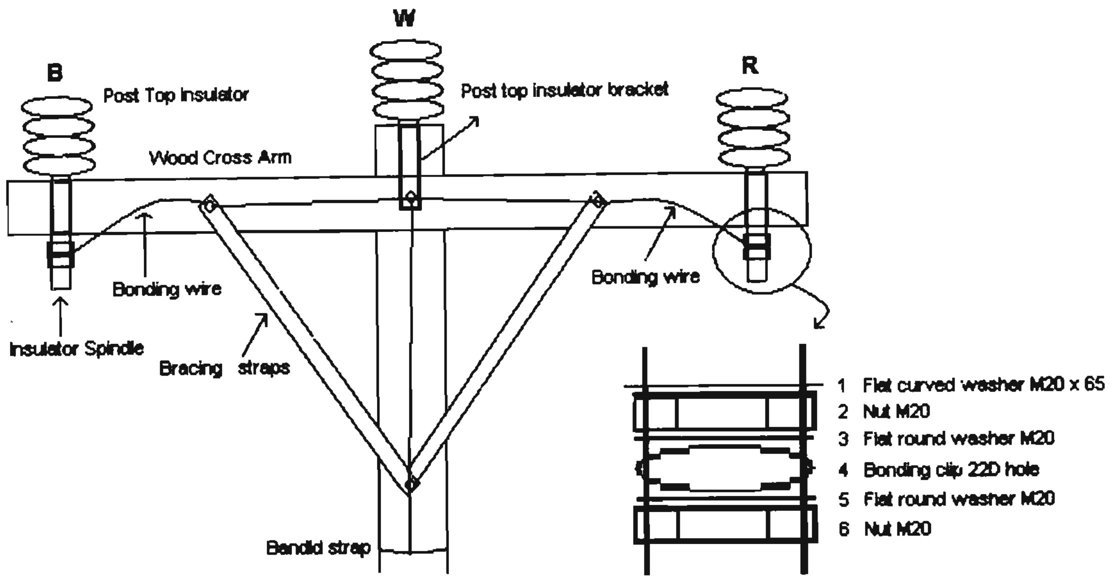


Figure 3 – 21: Bonding of all metal hardware and insulator "dead" ends on a common wood pole structure.

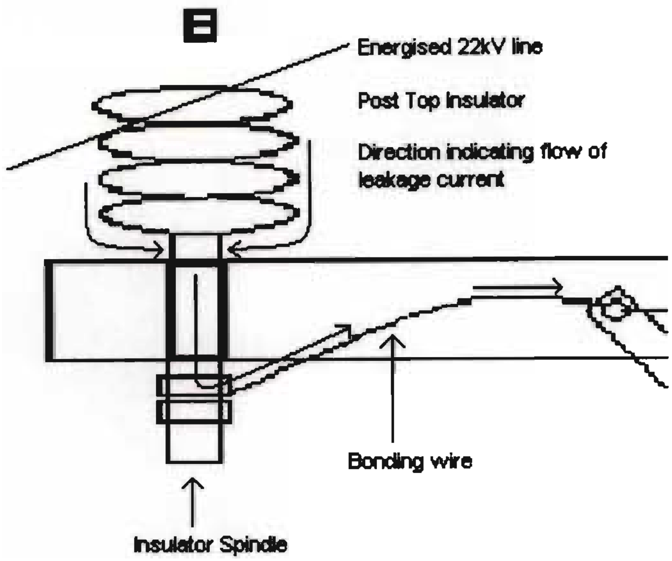


Figure 3 – 22: Flow of leakage current on a properly bonded cross arm (Persadh, 2003).

From the above figure, one can see the direction of flow of leakage current on a polluted insulator. With the base of the insulator insulated from the cross arm surface, the leakage current flows along the insulator surface and directly onto the spindle and not onto the cross arm surface. Note that the spindle has a lower resistance than that of the cross arm, hence from Ohms law, the current will flow into the spindle.

3.5.2.1 Electrical model of a bonded wood cross arm

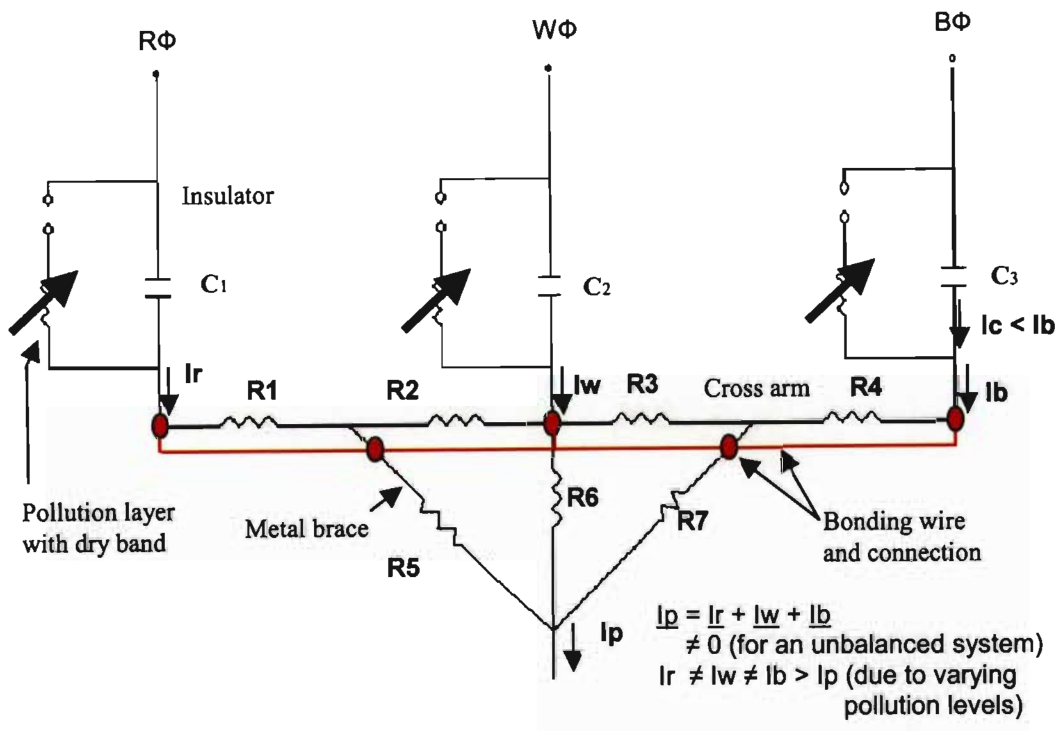


Figure 3 – 23: Electrical model of a bonded wood cross arm (Geldenhuys, 2004)

With a cross arm effectively bonded, unbalanced pollution related leakage currents flow away from the wood surface and onto the bonding wire as shown in Figure 3 – 23. The unbalanced resistive load (pollution layer) causes the potential of the bonding wire to rise with respect to the local pole "earth". This shall be further discussed in chapter four which critically analyses the performance of effective bonding.

3.5.3 Review of bonding design

In section 2.2 the researcher analyzed the various types of burning. In doing so, he critically examined the implementation of bonding in Eskom and in particular in KwaZulu – Natal. Over the next few years, Eskom's then Distribution Technology department continued to review designs and removed the copper bonding wire and replaced it with galvanized steel wire. Hence bonding materials subsequently consisted of only galvanized steel. At the time it was thought that the ideal design was attained. However, there existed other problems. Eskom Distribution Technology (DT) published drawings were incomplete. As per the principle discussed in section 3.5.2 and Fig 3 – 21 in particular, a washer was excluded on the one side of the bonding clip.

Further to this, the researcher had questioned the design of the bonding clip. The position of the M22 hole within the bonding clip was slightly inadequate to ensure a tight connection. These flaws also jeopardized the integrity of the electrical connections between the bonding wire and clips. Upon many site visits and project audits, the researcher had verified that this created a loose connection. The researcher had taken pictures of materials supplied by the manufacturers. These are illustrated below.

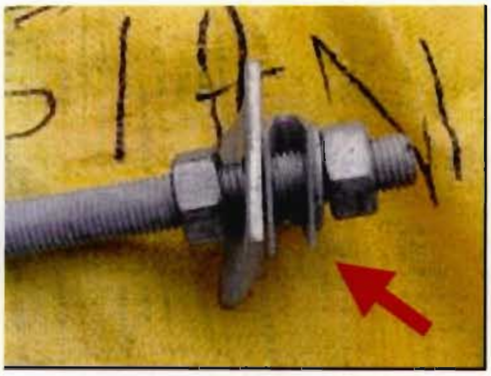


Figure 3 – 24: Inadequate materials supplied. A washer at the bonding clip was missing.

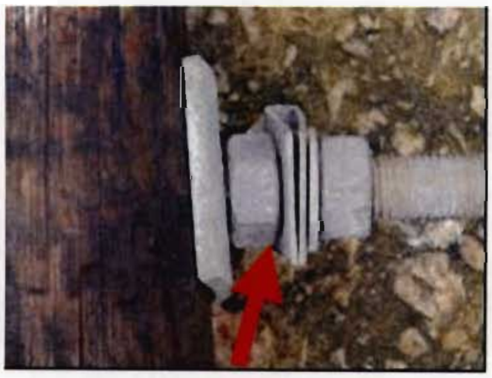


Figure 3 – 25: Linesmen failed to install the extra washer required to ensure a tight connection.

3.5.3.1 Current Designs

The current Eskom Distribution Eastern Region design is as illustrated in Fig 3 – 26. The design requires three strands of a $3.35mm^2$ galvanized wire that is effectively connected to all metal hardware and insulator "dead" end fittings. This bonding wire is passed through galvanized bonding clips of which is fastened to the spindles via galvanized M20 steel nuts and round flat washers on either side of the bonding clip. These designs have been implemented since 1999.

Figure 3 – 26: Effective bonding at one threaded rod on a cross arm.

3.5.4 Implementation of Current Designs

The researcher is employed in the Eskom Distribution Technology and Quality department. Since the year 2000, the researcher has been actively involved in implementing standards, specifications, procedures and guidelines. One such standard is the bonding of wood poles and cross arms. The researcher followed through and ensured that the standard is applied by taking the following measures:

- That all projects were to the latest design. Projects were Electrification, Reticulation and Refurbishment of medium voltage lines up to 33kV.
- Since designs were being standardized, the design packages were created and regularly updated.
- Training of project engineers on scoping of work on projects.
- That only approved manufacturers and suppliers were used to provide materials for projects.
- That only good quality material was used on projects as per specifications.
- Training of Eskom field personnel and approximately 700 contractor linesmen on the effective application of bonding.
- Auditing of projects of total capital expenditure exceeding R100m since 2001 to ensure compliance to standards.
- Hosting of and presenting in various forums such as the Clerk of Works Forum and Project Construction Quality Forum on albeit the bonding philosophy and application thereof.

Figure 3 – 27: An example of how effective bonding was implemented.

3.6 Summary of literature survey

The researcher shall now summarize the salient points gained from the literature above.
The mechanism of burning illustrates that the flow of sustained leakage currents from polluted line insulators onto a lightly polluted and wet wood cross arm surface can result in ignition of the wood. Furthermore, high voltage gradients or electric fields near energized metal fittings cause local discharges and current activity to penetrate the wood resulting in surface burning.

The controlling parameters for ignition in KZN included marine and industrial pollution which is aided by on – shore winds, high temperature and humidity levels and a subtropical coastal area with lots of fog banks and light drizzles that creates the necessary conductive paths for the leakage currents to flow. The other important factor is the specific creepage level of insulator used. Investigations concluded that a higher specific creepage level insulator (31mm/kV) be used in medium to heavily polluted environments such as KZN. Higher specific creepage insulators reduced the magnitude of pollution related leakage currents. It was also concluded that these insulators be used in conjunction with bonding so as to enhance specific insulator creepage levels. The controlling parameters are significant during winter and spring. This explains why the majority of burns have occurred over that period as can be seen from Figure 2 – 1.

Investigations in Kenya verified that an increased specific creepage level insulator reduced the magnitude of pollution related leakage currents. Following this, Eskom Distribution modified its insulator specification to require the use 31mm/kV specific creepage where severe pollution was experienced. Furthermore, wood cross arms were replaced with steel cross arms in areas where chronic burning was experienced. By implementing the above two methods, the Kenya Power and

Lighting Company almost completely eliminated the burning problem. However, with the use of steel cross arms, a small risk was identified. It was shown that burning could still occur where the steel cross arm bracing straps are attached to the main wood pole. Considering that there was little or no evidence of burning at the bracing interface with the pole in both Kenya and Eskom, investigators thought it wise to tolerate the low risk on existing structures. However, future installations required wrapping of a metal band or applying conductive paint around the pole at the bracing interface. This was to ensure that the brace-to-wood pole current density remains uniformly low.

The various laboratory investigations can be summarized as follows:

- Wood is an excellent insulating material when clean and dry. However, when the wood surface is lightly wetted the resistance decreases rapidly and higher leakage currents flow along it. This results in pollutants on the cross arm igniting. Hence, one of the main requirements for burning to occur is moisture which can be in the form of mist, light drizzle or high humidity.
- A clean dry cross arm and a lightly polluted insulator has a low effect on the circuit. The light pollution consisted of a mere 2% solution of Sodium Chloride. When the cross arm was moistened to simulate a light drizzle and with a mere 2% pollution severity on the insulator, a large leakage current of 3.5mA (at 9kV) started to flow causing sparks and ignition of pollutants to occur. Thus, one can appreciate the magnitude of leakage currents that would flow at 22kV. From this it can be seen that pollution severity becomes significant at a mere 2%. Hence severity of pollution has a major influence in the burning process.

- The pollution level on an insulator provides a resistive device that allows tracking of the line voltage. This explained why burning of cross arms in the field occurred on the onset of light drizzles and during times of heavy mist and high humidity levels.
- Leakage current activity on a cross arm can be reduced by applying a sheet of silicone around the cross arm and in series with the insulator. This sheet maintained a high resistance across the surface of the wood under high levels of pollution. Thus it prevented a path for high leakage currents to flow. Silicone has proved its excellent capabilities in maintaining a high resistance path and thus reducing leakage currents. However, due to the current skills shortages it is not practical to coat all existing porcelain insulators in the field with silicone to get the desired effect. It is however, practical to rather use silicone insulators.

- Voltage gradients are present on the surface of wood cross arms of energized structures. The voltage gradient increases closer to the line voltage or base of insulator.

From the investigations on alternative solutions to prevent pole top fires, all tests proved to be successful. However, not all are practical. The proposed methods cannot be easily applied on existing structures to achieve their desired effects. However, the method of guarding, which is explained in section 3.3.6.4, was considered as an alternative to bonding in areas where high lightning activity was present. This was not implemented though. The activity between the insulator spindle and inside of the wood cross arm needs to be further investigated.

The principle of bonding was illustrated and thought to be the most practical method to implement. Bonding was also thought to have the effect of reducing the chances of burning by diverting leakage currents away from the cross arm surface. However, investigations by the researcher highlighted the poor implementation of the bonding principle prior to the year 2000. This was critically examined in chapter two. Although there were reports of burning bonded cross arms, Eskom field staff did not produce evidence of an effectively bonded and burnt cross arm. Hence the reports of fires were dismissed as a result of poor bonding. There has always been strong belief in Eskom Distribution that properly bonded cross arms do not burn. Subsequent to the year 2000, the researcher was actively involved in implementing and monitoring the latest bonding design standards. These will be analyzed in the next chapter.

CHAPTER 4: CRITICAL ANALYSIS OF EFFECTIVE BONDING

Following various investigations, the researcher highlighted the poor implementation of bonding in KZN prior to the year 2000. Considering that the principle of bonding was the most practical to implement, Eskom in KwaZulu – Natal embarked on various initiatives to ensure that proper bonding was effectively implemented. As pointed out in section 3.5.4 above, the researcher has been actively involved in this implementation and shall now analyze the performance of effective or correct bonding in KZN.

4.1 Installation of effective bonding

4.1.1 Mhlatuze sites

During the year 2002, Eskom Distribution in KZN decided to benchmark the performance of effectively bonded wood cross arms against structures containing steel cross arms. Historically, the Empangeni Field Service Areas were mainly affected by the phenomenon of pole top fires. It was thought appropriate to use projects in the Empangeni area for this purpose. As such Mhlatuze and Nseleni areas were chosen. A few structures in the Mhlatuze area were refurbished to the latest standard of which bonding was a part. This included the use of 31mm/kV specific creepage line post **porcelain** insulators and 31mm/kV specific creepage **silicone long rod** type insulators.

The bonding was applied as per section 3.5.2. To ensure a proper benchmark, these structures were installed adjacent to structures that were experiencing burning of cross arms. Figure 3 – 26 and Figure 3 – 27 illustrate the above.

4.1.2 Nseleni sites

Nseleni network breaker 19 is a project that was completed in the year 2003. It was classified as a medium voltage line upgrade to 22kV and refurbishment and consisted of a combination of Mink conductor on the backbone and Fox conductor on the tee – offs. The first 4.2km of Mink backbone along a dusty road was designated for the piloting of steel cross arms. A total of 35 x 1.3m steel cross arms were installed with a mix of a number of 2.5m wood cross arms. The objective was to compare the performance of both steel and effectively bonded wood cross arms in an area troubled by pole top fires.

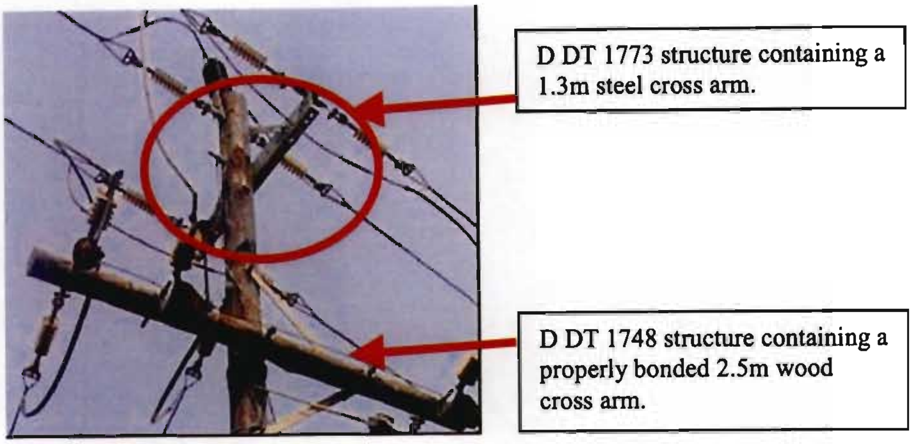


Figure 4 – 1: Mix of steel and wood cross arms installed at Nseleni late in 2002.

4.2 Follow up inspections

Once the above projects were completed, the researcher had inspected them and ensured compliance to Eskom's Distribution Technology standards. Of particular importance was the application of bonding and use of Eskom approved materials. Once again Figure 3 – 26 and Figure 3 – 27 bear testimony to the good bonding connections at Mhlatuze. Figure 4 – 1 also refers. The bonding was compliant to standards.

Incidentally, the researcher has been auditing projects since January 2001. One such project inspected in October 2005 was the refurbishment of a 22kV line beyond Esikhaweni network breaker 17. The performance of bonding on this network will briefly be discussed later.

4.3 Monitoring of Nseleni sites

Since the steel and wood cross arms were installed in the late 2002, the researcher maintained constant contact with the Empangeni TSC to monitor the performance of the structures. There were initial fears that the Mink conductor may clash at mid span due to the steel cross arms being short. However, to date there have been no incidences of clashing conductors on the spans with steel cross arms. Furthermore, Nseleni is noted for experiencing very high lightning activity. The sites were visited in June 2006 by the project designer viz. Lebone Consulting Engineers. Visual inspections were conducted **from ground level** on various structures and the following was reported.

- All of the steel cross arms were in good working order in terms of position, corrosion and bending.

- There was no evidence of tracking or burning at the interface between the metal bracing straps and the vertical wood pole surface.
- Although a considerable amount of dust pollution was evident on most of the steel cross arms, wood cross arms and silicone long rod type insulators, there was no physical evidence of tracking or burning on the wood cross arms.
- Lebone Engineering Consultants had concluded that the steel cross arm installations had performed satisfactory for a period of four years.

4.4 Researcher's findings

The researcher had inspected parts of Nseleni network breaker 19 in September and November 2006 respectively. As per the objectives of the project, only those structures that were refurbished and found compliant to standards were further inspected. Voltage and current readings for Nseleni network breaker 19 were taken at the substation to ascertain if any imbalance existed on the supply system. These are shown below.

Table 4 – 1: Nseleni N/B 19 voltage readings at the substation.

Phase	Voltage (kV)
Red phase	22.23
White phase	22.29
Blue phase	22.13

4.4.1 Inspections with a Pole Top Camera

Inspections during September 2006 were done via a digital Pole Top Camera. The camera was attached to an operating link stick and video recordings were done while the structures were energized at 22kV. It was difficult to get steady recordings as it was windy and this made the handling of the link stick difficult.

The following observations were made on a D DT 1848 (section link structure with 2.5m wood cross arm) and D DT 1733 (strain structure with a 1.3m steel cross arm) at T312L1:

- The wood structures were bonded to standard. There were no visible signs of tracking or leakage current activity on the wood cross arm surface. There were no visible signs of fire.
- The steel cross arm was still in a good condition. There were no visible signs of tracking or leakage current activity at the interface between the wood pole and steel cross arm.

- The pole was splintering at the through bolt between the wood pole and steel cross arm.
- The link cut outs were mounted onto the cross arm via brackets and threaded rods. Some of these brackets were slightly loose. The Eskom operator was able to move it with the link stick. This is an important finding and shall be discussed later.
- 22kV silicone long rod type insulators with specific creepage 31mm/kV and 22kV silicone rubber link cut outs with specific creepage 31mm/kV were used.
- The pollution level appeared heavy and looked even on all insulators although the area had experienced heavy rainfall a few weeks prior to this inspection. The line is along a dusty road.

4.4.2 Live – line inspections with a digital camcorder

Inspections during November 2006 were done via a digital camcorder. The researcher had arranged with the Eskom Live – Line department to assist in getting very close to the energized 22kV line to inspect and video record. Voltages were measured with respect to earth and were taken with a portable voltage tester (phasing sticks). Diagrams of measurement are illustrated below.

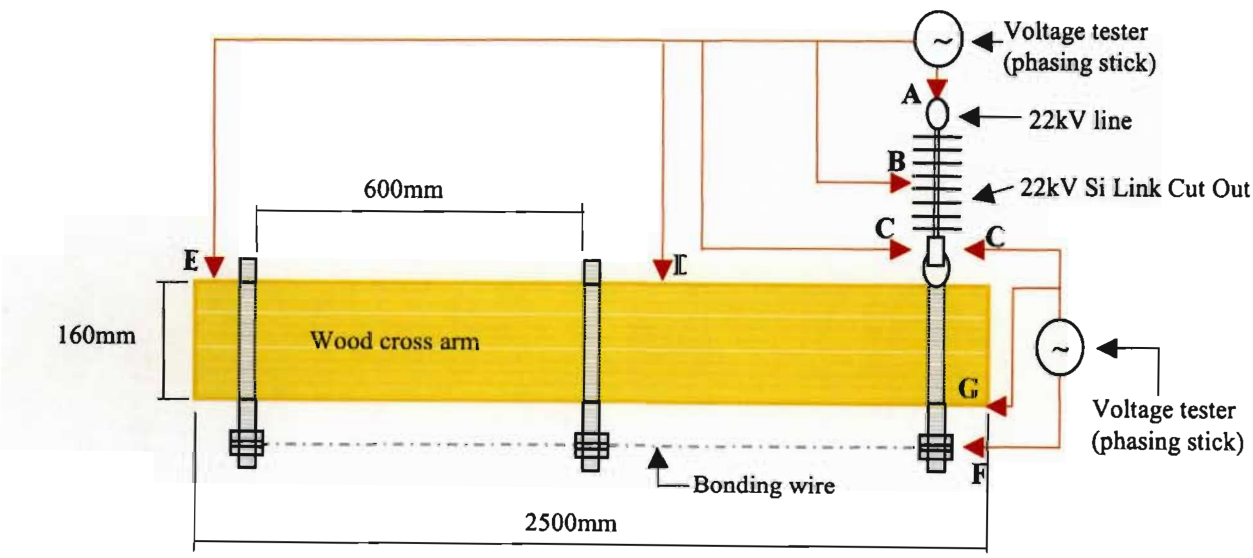


Figure 4 – 2: Diagram of measurement of voltages on a wood cross arm section link structure (D DT 1848) with Silicone long rod insulators.

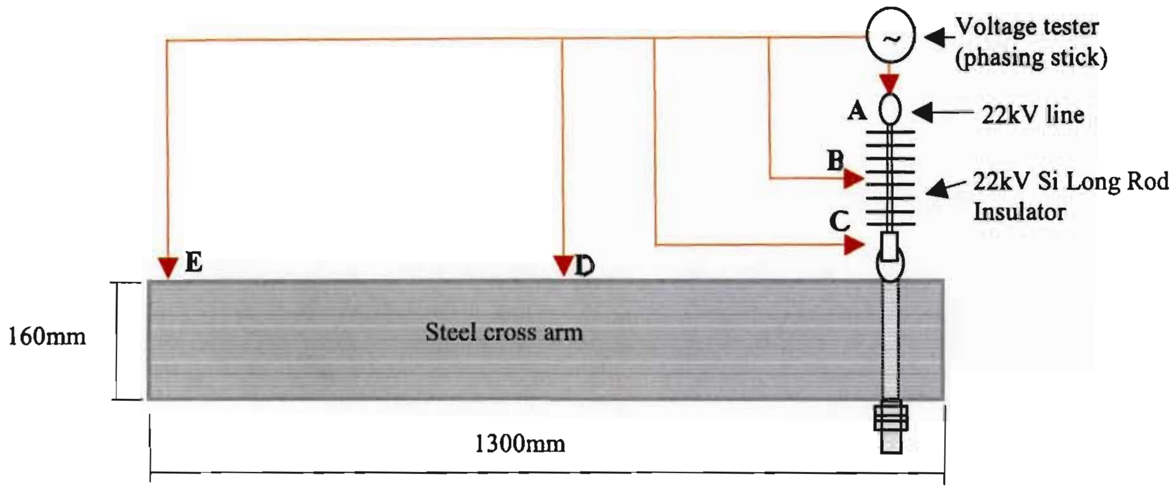


Figure 4 – 3: Diagram of measurement of voltages on a steel cross arm strain structure (D DT 1733) with Silicone long rod insulators.

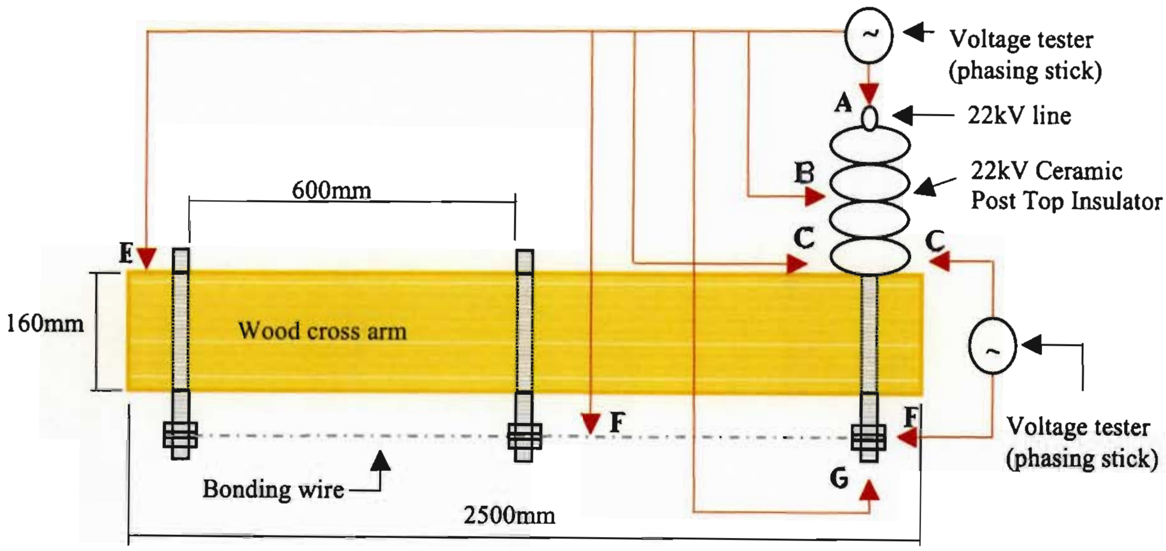


Figure 4 – 4: Diagram of measurement of voltages on a wood cross arm suspension structure (D DT 1740B) with Ceramic insulators.

The following voltage readings and observations were made on the above D DT 1848 (section link structure with 2.5m wood cross arm) and D DT 1733 (strain structure with a 1.3m steel cross arm) beyond T309L1: Figures 4 - 2 and 4 - 3 respectively has reference.

Table 4 – 2: Voltage readings taken at various points on the steel and wood cross arm structures.

Measurement Between Points	Voltage measured on Wood cross arm structure (kV)	Voltage measured on Steel cross arm structure (kV)
Live – middle of silicone link cut out (A-B)	2.7	
Live – end of silicone link cut out (A-C)	12.8	
Live – middle of cross arm wood surface (A-D)	6.5	12.8
Live – end of cross arm (A-E)	6.3	12.8
Bonding wire – wood cross arm surface (F-G)	0.3	
Bonding wire – stay wire	0.1	
Bonding wire – end of silicone link cut out (F-C)	2.4	
Live – middle of silicone long rod (A-B)		2.8
Live – end of silicone long rod (A-C)		12.5
Steel cross arm – wood pole	1.1kV	

The observations with the digital camcorder were the same as in 4.4.1. Note again that the same specific creepage silicone long rod type insulators and link cut outs were used. There were no signs of tracking or leakage current activity.

The researcher took the following voltage readings and made observations on a D DT 1740B (2.5m wood cross arm) structure beyond T2209L1. Measurements were done on a clear sunny and slightly windy day. Figure 4 – 4 has reference. The measurements are significant in that they verify that a voltage gradient exists along the wood cross arm.

Table 4 – 3: Voltage readings taken at various points on the wood cross arm.

Measurement Between Points	Voltage measured on Wood cross arm structure (kV)
Live – middle of **ceramic** insulator (A-B)	4.1
Live – end of **ceramic** insulator (A-C)	4.9
Live – end of cross arm (A-E)	6.9
Live – bonding wire (A-F)	12.7
Bonding wire - wood cross arm surface	0
Bonding wire – bottom of insulator (C-F)	0.3
Bonding wire – BIL down wire (earth)	0
Live – directly below insulator and cross arm (in air)	(A-G) 3

Figure 4 – 4 can be electrically modeled into that shown in Figure 4 – 5 below.

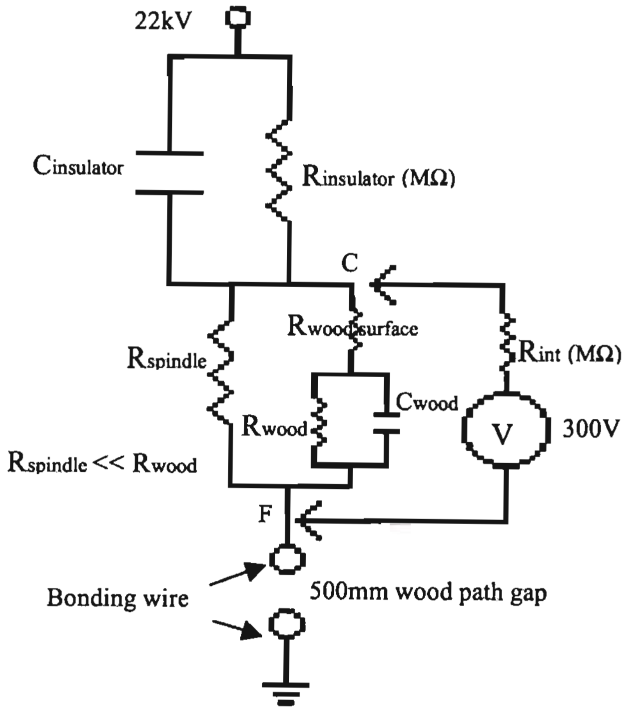


Figure 4 – 5: Electrical model of diagram of measurement with Ceramic insulators.

The 300V measured between points C and F appears to be suspiciously low. Note that point C is at the bottom end of the insulator. Considering that the voltmeter / phasing stick has a very high internal resistance which is in the range of mega ohms, the following explanation refers. The resistance of the insulator is in the range of mega ohms. Similarly, the resistance of the wood cross arm is very high (possibly in the range of mega ohms as well). The resistance of the spindle / threaded rod is far less than that of the wood. That is, $R_s << R_{wood}$. Hence, greater leakage current will flow from the insulator surface and into the spindle. This would yield a lower voltage drop. Therefore the low measured voltage is the voltage drop across the spindle.

However, if the researcher had measured between the surface of the wood cross arm and the bonding wire, the reading would have been much higher for the following reasons. Smaller amounts of leakage currents flow though the wood surface and meters internal resistance. Due to the wood surface and meter having much higher resistances, the voltage drop will be higher. Therefore the measured voltage would be a summation of the voltage drop across the wood surface and that across the meter.

The experiment was running since 2002. The following observations were made in November 2006:

- The wood cross arm was bonded 100% to standard.
- The structure was fitted with post top **ceramic** insulators of specific creepage 31mm/kV.
- These outer phase insulators were loose. The researcher was able to physically and easily rotate them with his hands.
- Traces of burning was observed on the cross arm at the outer phase insulator bases.
- There was evidence of tracking or leakage current activity between the insulator base and cross arm surface. This was evident at both insulators. The insulators did not have a metal base.
- Upon closer examination, the tracking had emanated from the insulator spindle oval shaped washer and onto the wood surface.
- There was a very thin and almost transparent layer of pollution on the sides of the insulators where the tracking was evident. The pollution appeared to be washing away onto the wood surface.

The following are pictures of the correctly bonded structure and show early signs of burning of the wood cross arm surface.

Figure 4 – 6: Live – Line inspection and voltage measurements on a D DT 1740B structure.

Figure 4 – 7: Early stages of tracking were observed between insulator base and wood surface.

4.4.3 Removal and inspection of steel cross arm structures

The steel cross arm structure in Figure 4 – 1 was retrieved from site and taken to Empangeni TSC for further inspections. The steel cross arm was disassembled from the wood pole structure and the wood was subsequently cross – sectionalized. The following observations were made in August 2007:

- Silicone long rod type insulators of specific creepage 31mm/kV were used on the steel cross arm.
- The threaded rods securing the steel cross arm and bracing straps to the wood pole were loose. This was due to the pole shrinking during the last five years.
- Heavy pollution was observed on all three silicone long rod insulators.
- The steel cross arm was still in very good condition.

- The bottom side of the steel cross arm was pressed tightly against the wood pole. There was little or no visible pollution on the pole at the bottom side of the steel cross arm. There was no evidence of surface tracking / sparking from the bottom side of the steel cross arm to the wood surface.
- The top side of the steel cross arm had a small air gap of approximately 3mm from the wood pole. There was evidence of pollution in this vicinity. There was also evidence of **very slight tracking / sparking** from the corner edge of the top side of the steel cross arm onto the wood surface.
- The threaded rod mounting the steel cross arm had no signs of burn marks / blackening effect. It was clean compared to a threaded rod / spindle that mounted a porcelain insulator where surface tracking / sparking was observed. This is illustrated in Figure 4 – 9 below.
- Upon sectionalizing the wood, there was no sign of burnt cavities / internal sparking inside of the wood.
- Also, there were no signs of surface tracking / sparking at the bracing straps and wood interface.

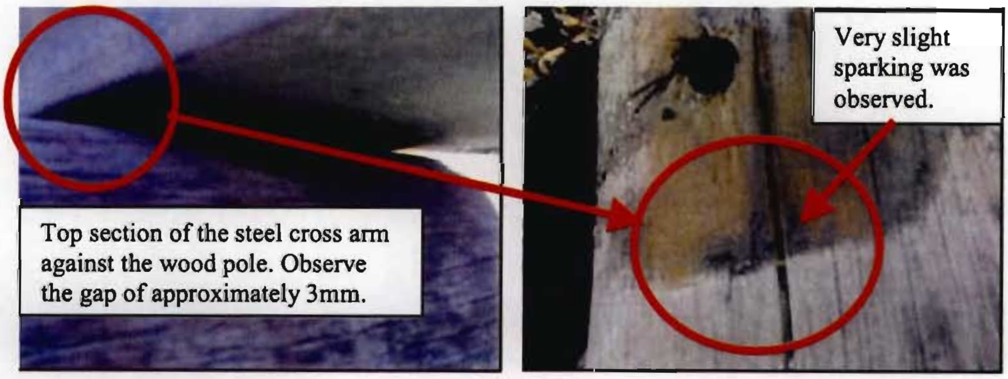


Figure 4 – 8: Illustration of tracking / sparking from steel cross arm to wood surface.

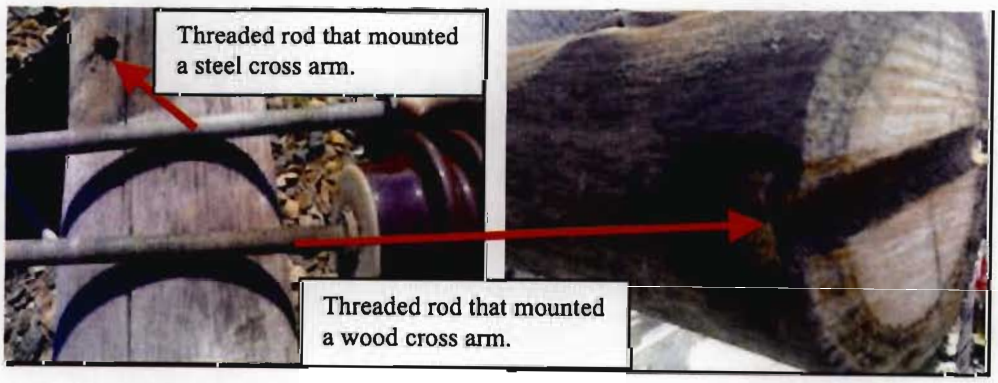


Figure 4 – 9: Comparison of threaded rods from different installations.

Another steel cross arm structure was also retrieved from site and inspected on the same day. The findings were similar to the first except that **no tracking / sparking** was observed between the wood and steel interfaces.

4.5 Findings beyond Esikhaweni N/B 17

Esikhaweni network breaker 17 feeds a line that was refurbished in 2005. Upon completion, the researcher had audited the project in October 2005. The bonding on most structures was found to be compliant to standards. However, during this same period in 2006 Eskom field personnel had attended to a breakdown beyond this feeder. They had found the following:

- A wood pole that was bonded to the latest standards had severely burned and subsequently broke off. The structure was a combination of D DT 1740B (suspension) and a D DT 1747 (in line strain)
- Post top **ceramic** insulators of specific creepage 31mm/kV were installed on the 1740B structure.
- There was no evidence of burning at or near the ceramic insulators.
- The burning was occurring at the bottom end of the one bracing strap of the D DT 1747 structure.
- 22kV silicone long rod type insulators with specific creepage 31mm/kV were installed adjacent to this bracing strap.
- Upon removing the threaded rod mounting the bracing strap, fire damage was observed inside the hole of the threaded rod.
- The burning had started from the inside of the pole.

The above findings are illustrated below.

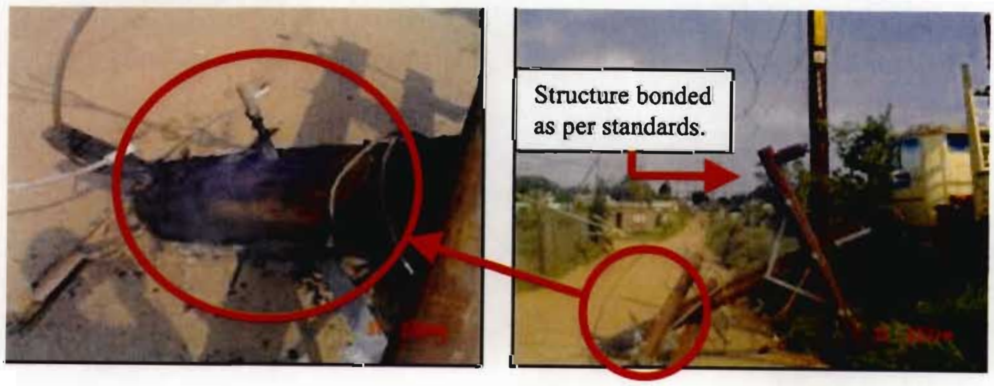


Figure 4 – 10: A burning bonded wood pole with smoke exiting a threaded rod hole.

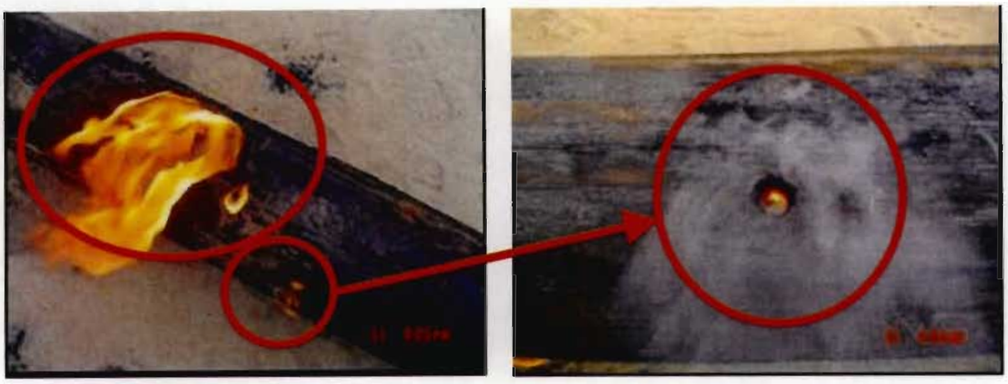


Figure 4 – 11: Flames exiting the threaded rod hole and at other crevices along the pole. Silicone link cut outs were closest to the affected area.

One can see the fire inside of the same threaded rod hole above when the rod was removed.

4.6 Analysis of findings

4.6.1 Performance of the silicone insulators

Although heavy dust pollution was observed on the long rod type silicone insulators at Nseleni, no leakage current activity was observed at or near the ends of these insulators. The same was observed at the Mhlatuze test site. This verified the results of the laboratory studies pointed out in section 3.3.4. The silicone had proved its excellent abilities in maintaining a high resistance path and thus reducing the leakage currents.

4.6.2 Voltage gradients and electric fields

The voltages measured at various points along the cross arm verified the laboratory measurements highlighted in section 3.3.5. Voltage gradients exist on the surface of wood cross arms of energized structures. With respect to the properly bonded D DT 1740B structure where burning was observed and from Table 4 – 3, the voltage measured between the bonding wire and bottom end of the porcelain insulator surface was 300V. Note that the bonding wire was electrically connected to the oval shaped washer which is part of the insulator spindle. Hence this 300V existed between the bottom end of the insulator surface and oval shaped spindle washer.

The washer has a sharp edge all around. This sharp edge leads non – uniform electric fields around the washer edge. With the washer energized at 300V, corona may occur around this edge. That is, self sustained electric discharges where the field ionizations are localized only over the non – uniform field. These discharges lead to sparking onto the wood surface and eventual burning of the external wood surface. Figure 4 – 13 bears testimony to this phenomenon. The sectionalized cross arm in the figure is from the same properly bonded D DT 1740B structure discussed in 4.4.2. The thickness of the washer is 5mm. Hence the distance from the base of the insulator to the wood surface is 5mm. Thus the electric field that exists in this vicinity is calculated to be: E = V/D

= 300V/5mm

= <u>60Vmm⁻¹</u>

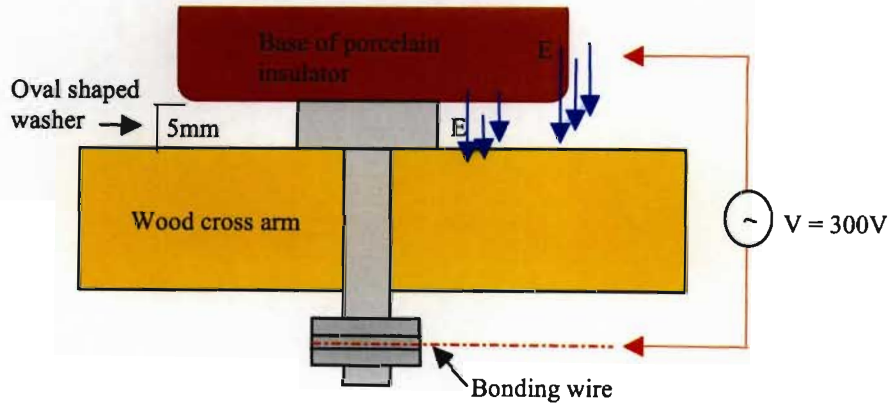


Figure 4 – 12: Diagram illustrating the electric field E from the oval shaped washer edge and insulator base.

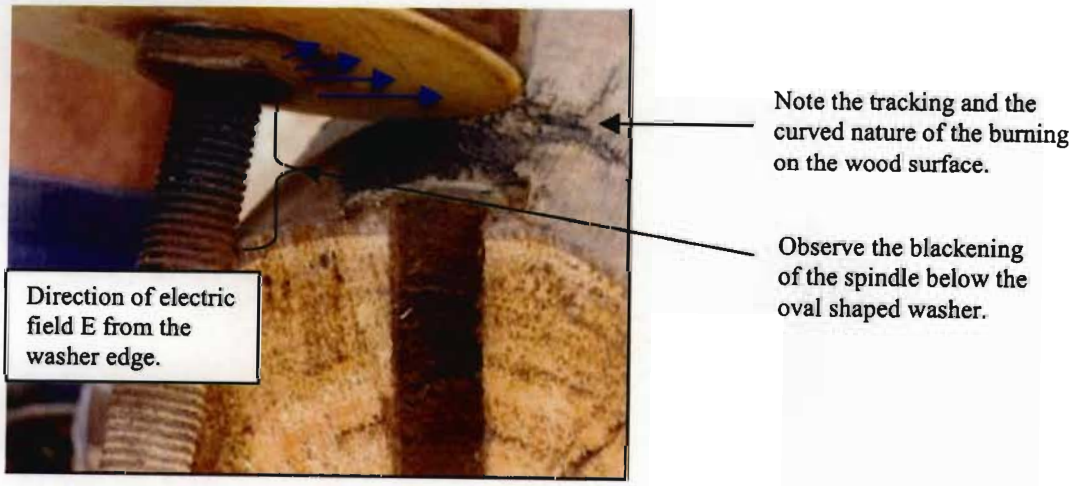


Figure 4 – 13: Sectionalized cross arm with spindle and insulator base showing direction of electric fields from spindle washer and tracking on the wood surface.

Due to dry band arcing and the dissimilar impedances of the three branches the potential of the bonding wire may be raised to such a voltage as to cause sparking.

4.6.3 External burning caused by sparking on a properly bonded wood cross arm

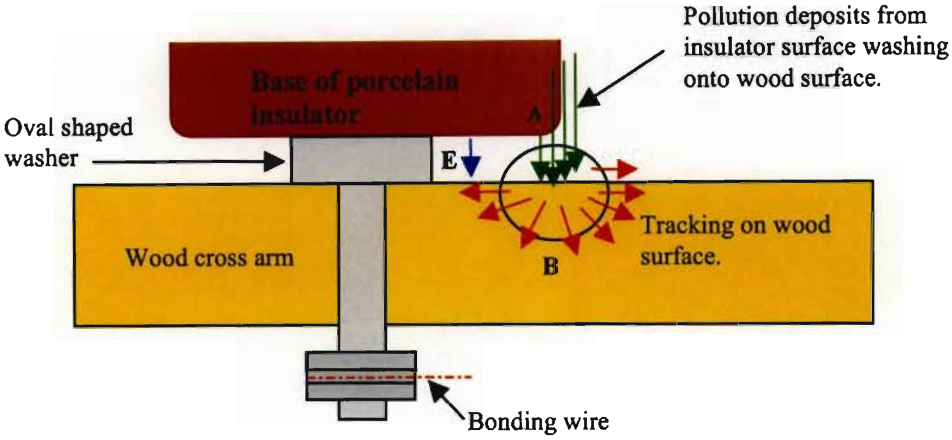


Figure 4 – 14: Diagram illustrating pollution deposits from insulator washed onto wood surface.

The above diagram further illustrates the burning mechanism as pointed out in Figure 4 – 13. Further to the explanation given in 4.6.2, pollution stains were observed at the base of the porcelain insulators. The pollution appeared to be washing away onto the wood surface and thus accumulating onto it. It is important to note that the edge (point A) of the base of these porcelain insulators is not as smooth as the insulator sheds. These rough edges lead to non – uniform electric fields. As pointed out in 4.6.3 above high electric fields exist between points A and B respectively. This resulted in sustained sparking between points A and B, thus causing the burning of the wood surface.

As can be seen in Figure 4 – 13, the burning is most severe directly beneath the base of the insulator. The pollution layers directly below the base were shielded from sunlight and kept dry. With the onset of light drizzle or heavy fog, this pollution layer becomes conductive and produces deep charred tracks which radiate in irregular patterns from the metal – wood connections. These tracks were observed on the surface of the wood. As pointed out previously, this needs to be further investigated. However, this demonstrates that effectively bonded wood pole structures with porcelain insulators can still burn.

Note that the burning does not start from the underneath of the cross arm where washers also with sharp edges are attached to the spindles. This is so because the pollution deposits on the underneath of the cross arm are far less concentrated and this section is most often kept dry. Pollution and light wetting were shown to be the biggest contributors to pole top fires.

4.6.4 Internal burning of the wood cross arm

A further finding on the D DT 1740B suspension structure was that the insulator spindles were loose. During its four years of service the cross arm had experienced some shrinkage resulting in the tightness of the spindles against the inside of the cross arm becoming weaker. The very fact that one was able to rotate the porcelain insulators by hand confirmed that the tightness was very weak. The author suspected that in this case, the wood cross arm was burning from within, that is between the insulator spindle and wood. Note that this arrangement would allow small amounts of air to flow between the spindle and wood.

The said cross arm was removed from site and sectionalized to ascertain any activity between the spindles and wood. Various cavities were observed on the spindle hole inside the wood. These are illustrated in Figure 4 – 15 below. Considering that the cross arm and spindle arrangement has a similar geometry as a cable, the author uses the co-axial geometry theory for cables in calculating the maximum electric field experienced at the threads of the spindle. Note that the cross arm spindle can be likened to the core of the cable. Calculations which appear in Appendix L reveal a high electric field strength of $14.43 Vmm^{-1}$. It is this high electric field that causes the air gap to breakdown resulting in sparking inside. Fire results if the sparking activity is sufficiently intense to bring the wood to its ignition temperature and if a sufficient air supply is available.

Figure 4 – 15: Illustration of cavities inside the wood cross arm.

The blackening of the spindles is indicative of the heat generated inside the cross arm. This intense heat would have been created by the sparking between the spindle thread edges and wood. Figures 2 – 16 to 2 – 20 and Figure 4 – 13 also bear testimony to this. It is standard arrangement to have a 500mm BIL gap on the above suspension structure down wire. However it was observed that structures without a BIL gap had experienced no burning. This is so because the bonding wire and spindles are connected to the earth via the BIL down wire and are at zero potential.

4.6.5 Performance of steel cross arms

As per Table 4 – 2, voltage gradients do not exist along the steel cross arm. However a potential of 1.1kV was measured between the steel cross arm and wood pole. The steel cross arm has a sharp corner along its side. As explained in section 4.6.2 electric fields exist between the steel and wood surface. This electric field combined with pollution deposits led to the relatively lower level of sparking from the steel to the wood surface.

The wood pole cross arms that displayed severe tracking / sparking were installed at the same time as the steel cross arms. However, the structures with steel cross arms had **very slight sparking** and can be managed / minimized by the application of fire retardant paint at the steel / wood interface. The fire retardant paint applied on the wood pole must cover the full surface area of the steel cross arm that makes contact with the wood. This paint will inhibit the sparking from burning the wood surface.

4.6.6 Loose Link Brackets

The loose link brackets is an important finding in that they have a direct impact on the internal burning of the cross arm. The link brackets are mounted onto the cross arm via threaded rods. As pointed out in section 4.1.2, the installation is four years old. During this period the cross arm had experienced some shrinkage resulting in the tightness of the threaded rod against the inside of the cross arm becoming weaker. The very fact that one was able to rotate the brackets with just a link stick confirmed that the tightness was very weak. This arrangement is similar to that in section 4.6.4 above and hence the same analysis holds.

4.6.7 The Esikhaweni structure

As pointed out in section 4.5, the structure was bonded to standard and the burning had occurred at the bottom end of one of the bracing straps of the D DT 1747 structure. Figures 4 – 10 and 4 – 11 refer. This was indeed a rare find and this time field personnel could not explain the phenomenon. The structure was approximately a year old. The burning can only be attributed to neutral shift which is explained in Annexure B.

4.6.8 Conclusion on the analysis of effective bonding

Proper bonding has been effectively implemented in an area prone to pole top fires. However, within four years of service, it was found that effectively bonded wood cross arms with porcelain insulators still burn.

The mechanisms of burning can be summarized as follows:

- Internal burning due to high electric fields between the spindle thread and wood causing sparking.
- External burning due to high electric fields between the spindle washer edge and wood surface causing sparking.
- These high electric fields are essentially due to the leakage currents that are present **on the bonding wire**, spindles and washers mounted at the base of the porcelain insulators. These leakage currents do not flow to ground because of the 500mm BIL gap present in the BIL down wire and hence raises the potential of these line hardware. It is this potential difference that creates the high electric fields and subsequently causes sparking.
- Burning due to the phenomenon of a neutral shift which cannot be avoided in highly polluted areas.

Hence, effectively bonded wood structures with porcelain insulators of specific creepage $31 mmkV^{-1}$ will not eliminate cross arm burning. The design of the oval shaped spindle washer and porcelain insulator base edge needs to be evaluated and further investigations carried out. The performance of porcelain insulators were not investigated with steel cross arms. This needs to be investigated. Silicone insulators have proved their excellent abilities in maintaining a high resistance path and thus reduced leakage currents. Thus post top silicone insulators should be considered in place of post top porcelain insulators. The shrinkage of cross arms resulting in loose threaded rods and insulator spindles has also played a role in the burning mechanism. To prevent burning due to this mechanism, one would have to regularly tighten nuts and spindles on structures.

However, this is not practical and hence not a solution. The steel cross arms piloted have outperformed the effectively bonded cross arms.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Power lines across the world carry a potentially lethal product and if not managed carefully can have serious legal, financial, safety, publicity and environmental risks. 22kV wood pole structures that support this product in KwaZulu – Natal have been shown to be vulnerable to the phenomenon of pole top fires. This has resulted in serious damage to the wooden infrastructure. The risks pointed out above consequently became a reality and Eskom Distribution came under constant pressure to find solutions to mitigate pole top fires. This research has provided an understanding of pole top fires and assessed the practicable preventative measures.

5.1.2 The researcher has revealed accurate statistics of the phenomenon on only 22kV overhead power lines in KwaZulu – Natal. The subtropical north coastal area of KZN which experiences higher relative humidities and temperatures and greater pollution have been shown to be affected the most. The majority of incidents has occurred over the winter and spring seasons. These seasons apparently have a direct influence on the burning mechanism. Veld fires, sugar cane burning, industrial pollution, dust and marine pollution, high temperature and high relative humidities combined with a set of weather patterns unique to KZN are the driving forces that contribute to the burning mechanism.

5.1.3 In analyzing the various types of burning that had occurred over the last decade, the researcher highlighted the poor implementation of bonding and speculated that many effectively bonded cross arms started burning from the inside and that this was possibly due to a neutral shift. The literature review also points out voltage gradients that exist along a wooden cross arm. These voltage gradients maintain high electric fields between rough metal brackets and the wood surface resulting in sustained sparking onto the wood surface causing burning. Samples of such cross arms were found by the researcher. The researcher also pointed out that many of the fires were experienced on poorly bonded or un – bonded structures with mainly ceramic type insulators of varying specific creepage per structure.

5.1.4 Many investigations in the 1990's revealed the effects of leakage current activity and the influence of insulator specific creepage on leakage current. These investigations highlighted the need for higher insulator specific creepage levels for coastal and heavily polluted areas. They also concluded that higher creepage insulators be used in conjunction with bonding. Eskom Distribution in KwaZulu – Natal heeded this advice and only insulators of specific creepage 31mm/kV were used since 2001. This however did not eliminate the burning as was pointed out in chapter 4 section 4.6.3. Further investigations in Kenya showed that the use of steel cross arms almost completely eliminated the burning problem. Laboratory studies have shown that one of the main requirements of the mechanisms of burning is moisture which can be in the form of mist, light drizzle or high humidity. This explained why burning of cross arms in the field occur on the onset of light drizzles and during times of heavy mist and high humidity levels.

5.1.5 The principle of bonding was illustrated and initially thought to be the most practical method to implement. Bonding was also thought to have the effect of reducing the chances of burning by diverting leakage currents away from the cross arm surface. However, investigations by the researcher highlighted the poor implementation of the bonding principle prior to the year 2000. This was critically examined in chapter two. Although there were reports of burning bonded cross arms, Eskom field staff did not produce evidence of an effectively bonded burnt cross arm. Hence the reports of fires were dismissed as a result of poor bonding. There has always been strong belief in Eskom Distribution that properly bonded cross arms don't burn. Subsequent to the year 2000, the researcher was actively involved in implementing and monitoring the latest bonding design standards.

With the above in mind the researcher critically analyzed effective bonding in KwaZulu – Natal. This required proper implementation and close monitoring of various sites. Steel cross arms were also piloted in these sites to bench mark the performance with effectively bonded wood cross arms. The analysis was an eye opener as the researcher found that effectively bonded wood cross arms with **porcelain insulators** still burn. This was attributed to a neutral shift and the existence of high electric fields between the spindles and wood surfaces. Effectively bonded wood structures with porcelain insulators of specific creepage $31 mmkV^{-1}$ does not eliminate cross arm burning. The method of bonding does not prevent pole top fires on wood cross arms with porcelain insulators.

5.2 Recommendations

5.2.1 The literature review has also demonstrated the excellent capabilities of silicone in reducing leakage currents. Investigations that were conducted on leakage currents had mostly included the use of existing ceramic type insulators which have been used in the field. It will be of great advantage in making a comparison between the EP965 insulator and a polymeric insulator. Hence it is recommended that further investigations be done with these insulators in the northern KwaZulu – Natal area. This would provide new technical evidence as to a possible alternative to bonding.

5.2.2 A number of alternative solutions to prevent cross arms from burning were also investigated in the 1990's. Although the results of investigations proved to be successful in preventing pole top fires, not all are practical to implement. The methods that were proposed need to be applied easily with long lasting capabilities and that application is not practical. The method of guarding is promising as it was seen to prevent burning. It was also considered an alternative to bonding in areas where high lightning activity is present. However, as pointed out in the literature review, it is recommended that the activity between the insulator spindle and inside of the wood cross arm be further investigated together with the method of guarding. Investigations are to include infrared scanning or the use of some newer technology to assess the heat of the insulator spindles or threaded rods.

5.2.3 The combined phenomena of neutral shift and the effect of electric fields on a wooden cross arm have not been investigated and need further investigation. The insulator oval shaped spindle washer and porcelain insulator base edge resulted in high electric fields forming around them. It is recommended that the components which enhance the electric fields be re-designed. Their design needs to be evaluated and further investigations carried out.

5.2.4 Silicone insulators have proved their excellent capabilities in maintaining a high resistance, hydrophobic path and thus reduced leakage currents below the 1mA range. Thus post top silicone insulators should be considered in place of post top porcelain insulators. An important finding is that burning does not occur on wood cross arms with silicone rubber insulators.

5.2.5 The shrinkage of wood cross arms resulting in loose threaded rods and insulator spindles has also played a role in the burning mechanism. This also requires further investigation.

5.2.6 The steel cross arms with silicone insulators that were piloted at Nseleni have outperformed the effectively bonded wood cross arms. Very slight sparking was observed between the steel and wood interfaces. Hence a recommendation that Eskom can consider is that steel cross arms be used in place of wood cross arms. An Eskom design using steel cross arms already exist and implementation thereof should be relatively easy. However, the steel cross arm need to be re-designed with rounded corners so as to reduce non-uniform fields that cause electric fields. Practically, retrofitting of steel cross arms are not necessary; however when cross arms do burn, Eskom can consider replacing them with steel cross arm equivalents during maintenance. Also, investigations need to be done with the combination of steel cross arms and porcelain insulators. This has not been done before.

5.2.7 Having recommended the above, there is a low risk of leakage current activity or high electric fields at the steel cross arm and wood interface. The steel cross arm is usually installed onto the pole via a threaded rod. It has been shown that high electric fields inside the wood between the threaded rod and wood result in sparking which causes the wood to eventually burn. It is recommended that fire retardant paint be applied inside of the threaded rod hole on the pole and left to dry before installing the cross arm. The same applies at the bottom end of the bracing strap that supports the steel cross arm. The fire retardant paint should also be applied at the steel / wood interfaces. This paint should be applied around the wood pole and must cover the full surface area of the steel cross arm and steel bracing strap that makes contact with the wood. The paint will inhibit the sparking from burning the wood surface.

5.2.8 To further reduce the risk of burning activity inside of the pole at the above points, a recommendation is that the steel cross arm and bracing straps be installed via U – bolts. A specially designed U – bolt will be required at the bottom end of the bracing straps. These need to be evaluated and designed accordingly.

5.2.9 Considering that wood poles undergo shrinkage, it is recommended that structures with steel cross arms and fire retardant paint applied be re-visited at least five years after first installation and every ten years thereafter. The idea is to re-tighten all loose threaded rods and maintain the effectiveness of the fire retardant paint.

5.2.10 Porcelain insulators were not piloted with the steel cross arms. Further investigations need to be conducted to ascertain the performance of steel cross arms with porcelain insulators of specific creepage 31mm/kV.

APPENDIX A 1

DURBAN ESKOM DISTRIBUTOR	# ENGINEERING INSTRUCTION		
	DATE: 10 March 1993	REF. RLC/10	ENQ. R T Green

BONDING OF MEDIUM VOLTAGE STRUCTURES

Recent problems in various areas in the Distributor have highlighted the fact that all Medium Voltage lines should have their hardware bonded. **This applies to all new line construction, and all lines that undergo rehabilitation.**

The details of the bonding are as follows :

1. Bond the hardware of the three phases together. On structures with crossarms this will be on the crossarm, and on vertical structures this will be on the pole. In accordance with the new Reticulation Technology Guide, use galvanized steel stay wire (3/3,35) and earth wire retaining clamps.

2. If capless post insulators have been used, the leakage path between the edge of the base of the insulator and the spindle will be along the crossarm, leading to probable heating. To avoid this, it will be necessary to insert a slotted (16mm) galvanized steel disc (about 2 mm x 110 mm diameter) between the base of the insulator and the crossarm to provide an alternative leakage path. The disc must be inserted with the slot perpendicular to the centre line of the crossarm.

3. To achieve a BIL of 300 kV on all structures on the line, structures must be modified in the following way:

Non-stayed structures:	Run a bonding wire up the pole, terminating 500 mm below the bonding of the three phases.
Stayed structures :	As above, but also introduce 260 kV BIL stay insulators in place of the guy strain insulators currently used.

For a graphic description, see attached drawing no. D-EN-900904. Please note that **every structure** in the entire line must be insulated to a 300 kV level for the concept to be most effective. This philosophy is contained in the Reticulation Technology Guide.

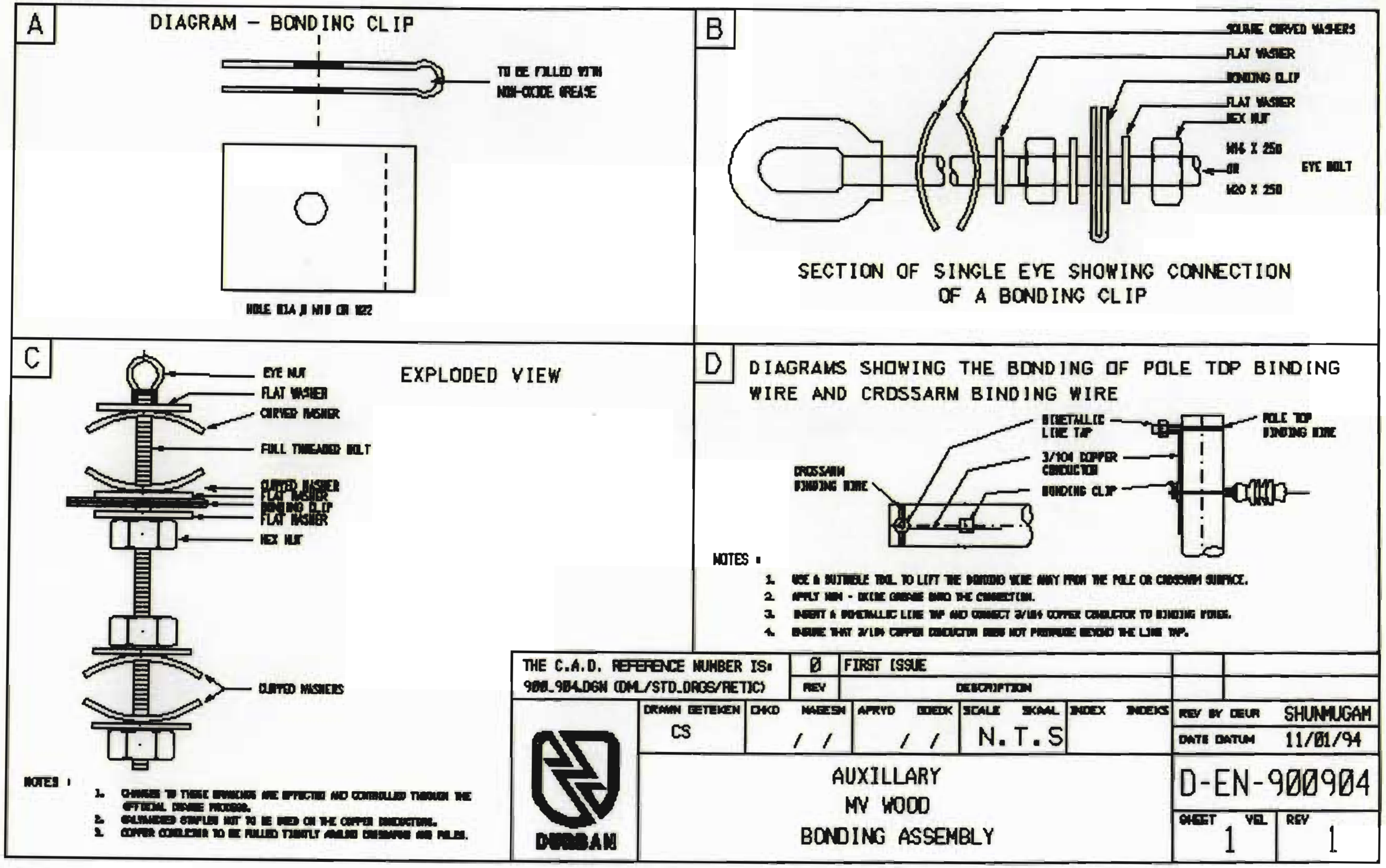
Should you require any further information, please contact:

Power System Technology Manager
26 Valley View Road, New Germany
Tel. (031) 710-5367
Fax. (031) 701-5995
Profs A71816 or FERGUSOA

R D MACFARLANE
ENGINEERING MANAGER – DURBAN DISTRIBUTOR

RTG/rtg

APPENDIX A 2


A
DIAGRAM - BONDING CLIP
TO BE FILLED WITH NON-OXIDE GREASE
HOLE DIA Ø M18 OR M22
B
SQUARE CURVED WASHERS
FLAT WASHER
BONDING CLIP
FLAT WASHER
HEX NUT
M16 X 250 OR M20 X 250
EYE BOLT
SECTION OF SINGLE EYE SHOWING CONNECTION OF A BONDING CLIP
C
EXPLODED VIEW
EYE NUT
FLAT WASHER
CURVED WASHER
FULL THREADED BOLT
CURVED WASHER
FLAT WASHER
BONDING CLIP
FLAT WASHER
HEX NUT
CURVED WASHERS
NOTES :
1. CHANGES TO THESE DRAWINGS ARE EFFECTED AND CONTROLLED THROUGH THE OFFICIAL CHANGE PROCESS.
2. GALVANISED STAPLES NOT TO BE USED ON THE COPPER CONDUCTORS.
3. COPPER CONDUCTOR TO BE PULLED TIGHTLY ALONG CROSSARMS AND POLES.
D
DIAGRAMS SHOWING THE BONDING OF POLE TOP BINDING WIRE AND CROSSARM BINDING WIRE
BIMETALLIC LINE TAP
POLE TOP BINDING WIRE
3/104 COPPER CONDUCTOR
CROSSARM BINDING WIRE
BONDING CLIP
NOTES :
1. USE A SUITABLE TOOL TO LIFT THE BONDING WIRE AWAY FROM THE POLE OR CROSSARM SURFACE.
2. APPLY NON - OXIDE GREASE ONTO THE CONNECTION.
3. INSERT A BIMETALLIC LINE TAP AND CONNECT 3/104 COPPER CONDUCTOR TO BINDING WIRES.
4. ENSURE THAT 3/104 COPPER CONDUCTOR DOES NOT PROTRUDE BEYOND THE LINE TAP.
THE C.A.D. REFERENCE NUMBER IS: 900_904.DGN (DML/STD_DRGS/RETIC)
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REV BY DEUR SHUNMUGAM
DATE DATUM 11/01/94
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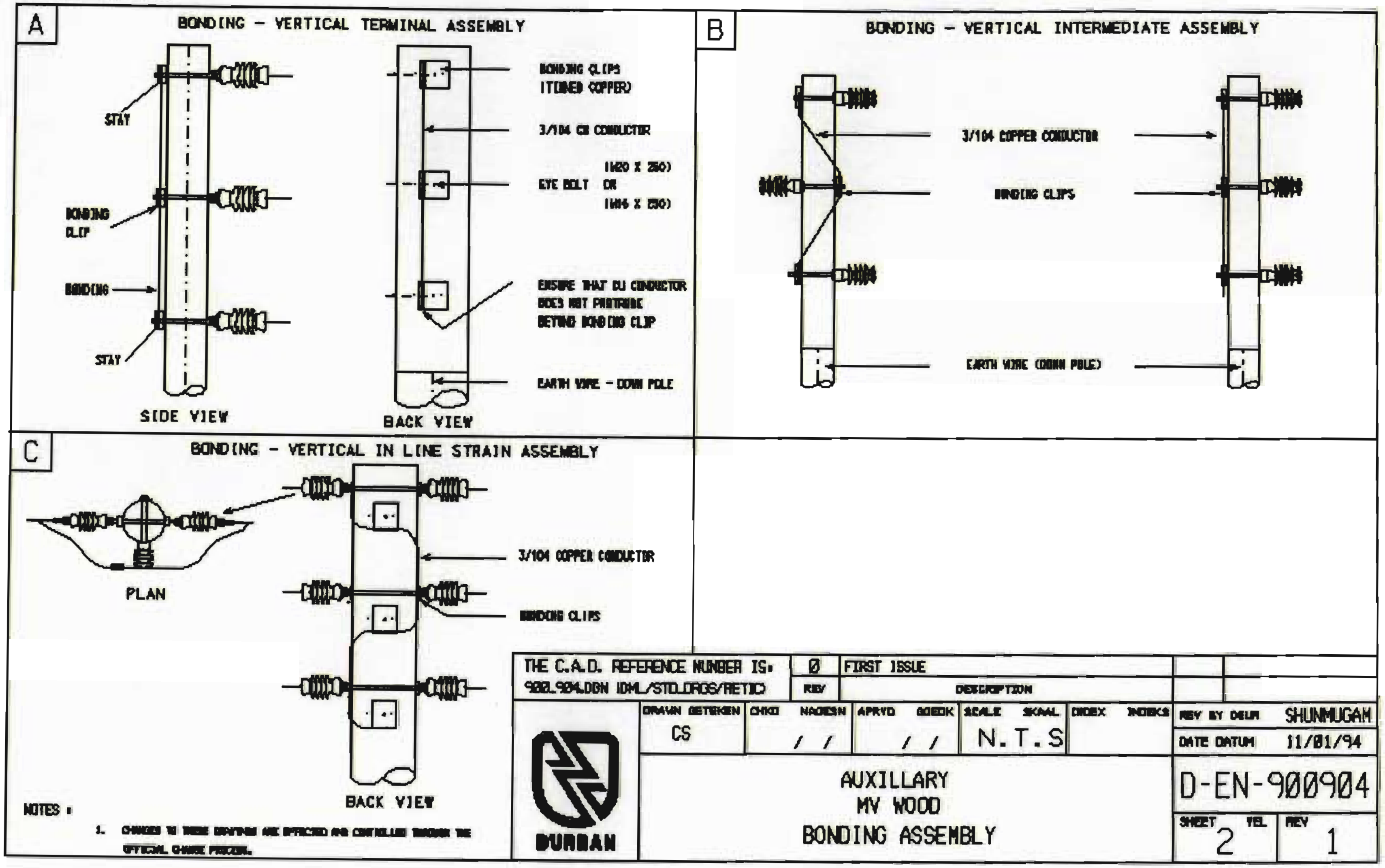
AUXILLARY MV WOOD BONDING ASSEMBLY
D-EN-900904
SHEET 1
VEL
REV 1

APPENDIX A 3


A
BONDING - VERTICAL TERMINAL ASSEMBLY
STAY
BONDING CLIP
BONDING
STAY
SIDE VIEW
BONDING CLIPS (TINNED COPPER)
3/104 CU CONDUCTOR
EYE BOLT (M20 X 250) OR (M16 X 250)
ENSURE THAT CU CONDUCTOR DOES NOT PROTRUDE BEYOND BONDING CLIP
EARTH WIRE - DOWN POLE
BACK VIEW
B
BONDING - VERTICAL INTERMEDIATE ASSEMBLY
3/104 COPPER CONDUCTOR
BONDING CLIPS
EARTH WIRE (DOWN POLE)
C
BONDING - VERTICAL IN LINE STRAIN ASSEMBLY
PLAN
3/104 COPPER CONDUCTOR
BONDING CLIPS
BACK VIEW
NOTES :
1. CHANGES TO THESE DRAWINGS ARE EFFECTED AND CONTROLLED THROUGH THE OFFICIAL CHANGE PROCESS.
THE C.A.D. REFERENCE NUMBER IS: 900.904.DGN (DML/STD.DRGS/RETIC)
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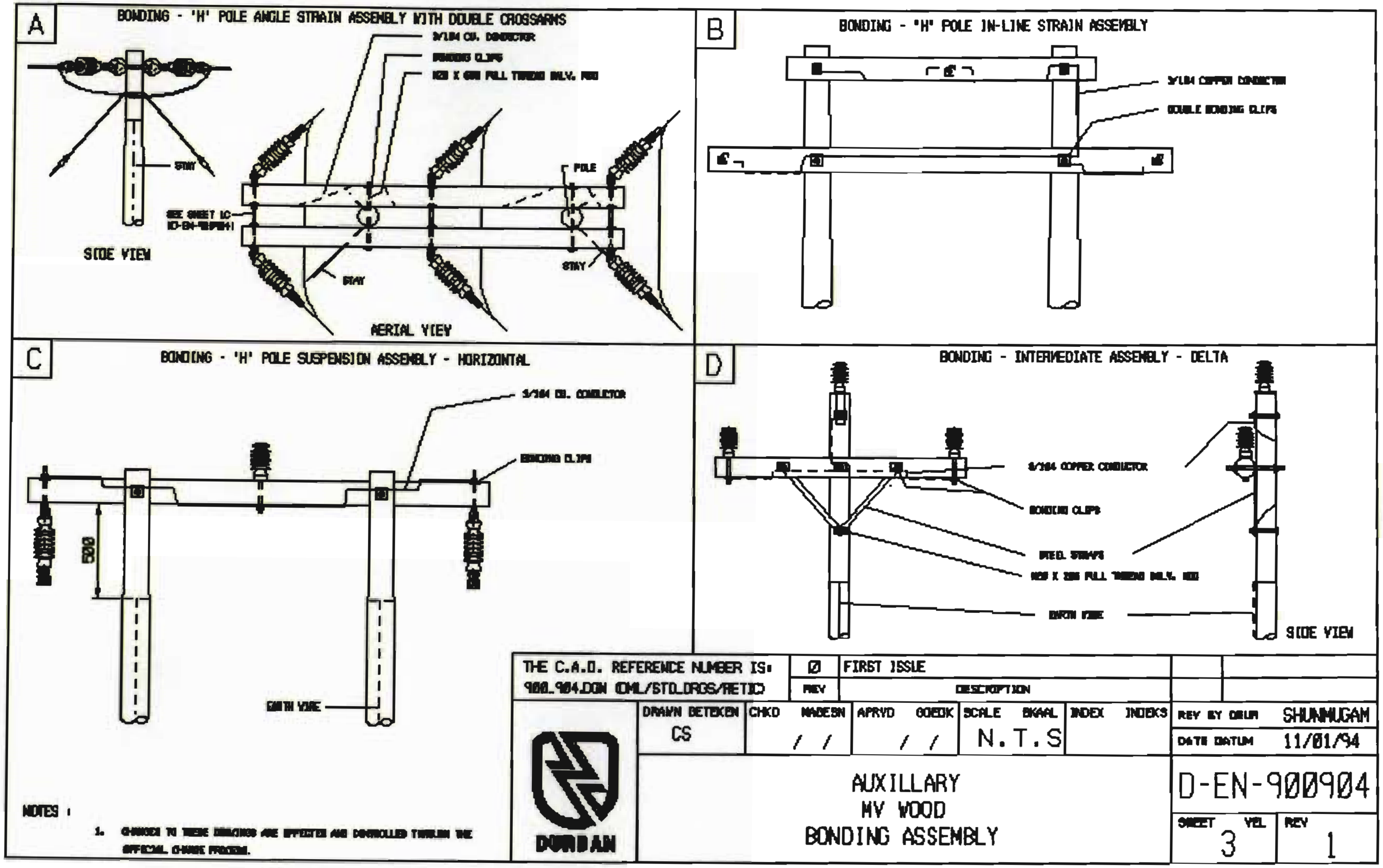
SHUNMUGAM
DATE DATUM
11/01/94
DURBAN
AUXILLARY
MV WOOD
BONDING ASSEMBLY
D-EN-900904
SHEET VEL
2
REV
1

APPENDIX A 4



A
BONDING - 'H' POLE ANGLE STRAIN ASSEMBLY WITH DOUBLE CROSSARMS
STAY
SIDE VIEW
POLE
STAY
AERIAL VIEW
B
BONDING - 'H' POLE IN-LINE STRAIN ASSEMBLY
3/104 COPPER CONDUCTOR
DOUBLE BONDING CLIPS
C
BONDING - 'H' POLE SUSPENSION ASSEMBLY - HORIZONTAL
3/104 CU. CONDUCTOR
BONDING CLIPS
500
EARTH WIRE
D
BONDING - INTERMEDIATE ASSEMBLY - DELTA
3/104 COPPER CONDUCTOR
BONDING CLIPS
STEEL STRAPS
EARTH WIRE
SIDE VIEW
NOTES :
THE C.A.D. REFERENCE NUMBER IS:
900_904.DGN (DML/STD.DRGS/RETIC)
Ø
FIRST ISSUE
REV
DESCRIPTION
DRAWN BETEKEN
CS
CHKD
NAGESN
APRVD
GOEDK
SCALE
SKAAL
N.T.S
INDEX
INDEKS
REV BY DEUR
SHUNMUGAM
DATE DATUM
11/01/94
DURBAN
AUXILLARY
MV WOOD
BONDING ASSEMBLY
D-EN-900904
SHEET
3
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REV
1

APPENDIX B: Explanation of Neutral Shift

Consider a properly bonded wood cross arm. Figure B – 1 below refers.

- Resistances of the wood cross arm are not taken into consideration as bonding wire is present.
- However, varying amounts of pollution across each phase insulator contribute to the variable resistance across each insulator. Thus the impedances are non-linear and the leakage currents contain harmonics.
- Hence there exist resistances R_R, R_W and R_B or Admittances Y_R, Y_W and Y_B respectively. R_N is the high resistance (or Y_N - admittance) of the 500mm wood gap. These are indicated in the figure below.

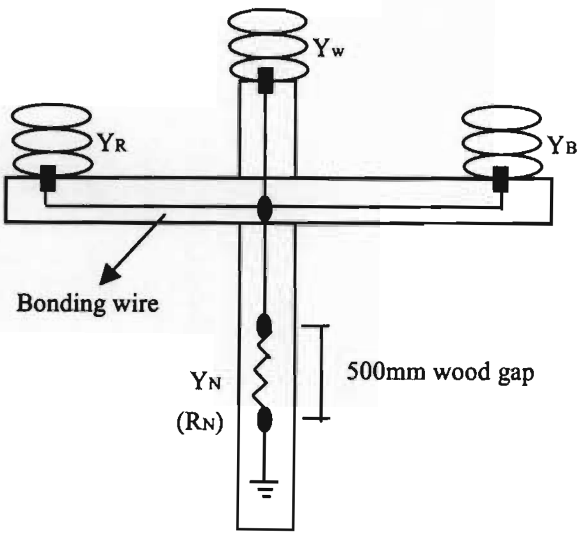

Figure B – 1: Diagram of a bonded cross arm

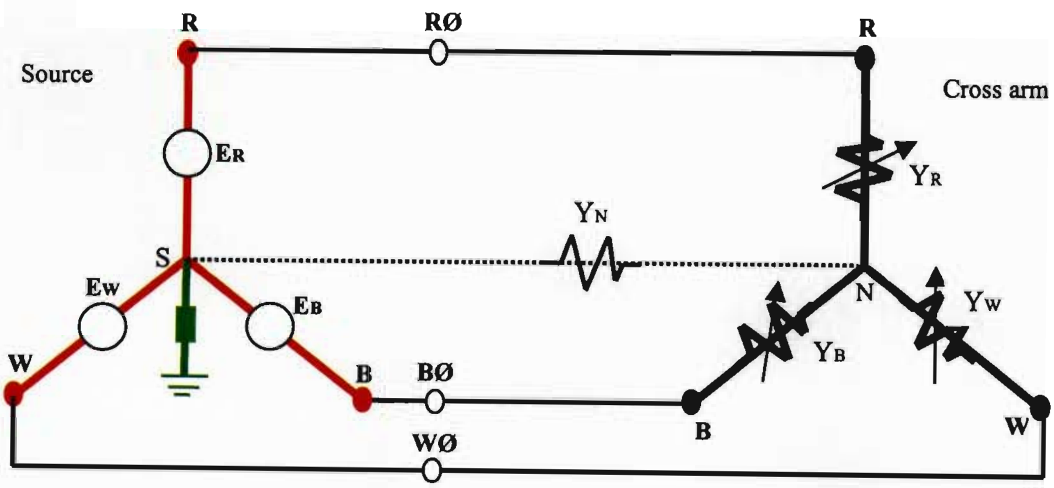

Figure B – 2: Electrical model of the bonded cross arm above.

- Assume that all the insulators are of the same type and with the same insulator specific creepage level. If the pollution layer on all these insulators is exactly the same, then: $Y_R = Y_W = Y_B$ and Y_N is negligible.

Then, the voltage between the supply earth and the cross arm earth V_{SN} is given by:

$$V_{SN} = \frac{E_R Y_R + E_W Y_W + E_B Y_B}{Y_R + Y_W + Y_B + Y_N}$$

$$= \underline{0}$$

Note that if the admittances are equal and the supply voltages balanced, V_{SN} will always be zero.

- This is the ideal situation to have. However, the pollution layer is not always the same on all three insulators and hence $Y_R \neq Y_W \neq Y_B$ and as such V_{SN} cannot equate to zero. In practice a small neutral voltage will usually exist. This applies only when the pollution is conductive, that is in wet conditions only.
- This unbalanced resistive load (pollution layer) causes the potential V_{SN} to rise with respect to the local pole earth. Note that the pole itself has a finite resistance to true earth and hence forms the earth of the supply system. In extreme pollution conditions, this may cause the bonding wire to reach a potential of several kV for short periods.
- This potential difference creates a high electric field to exist between the bonding wire and wood surface or between the inside of the insulator spindle and inside of the wood cross arm. It is this high electric field that causes sparking between these surfaces and consequently burning to start from inside of the cross arm.
- Since $V_{SN} \neq 0$, this implies that the phase voltages will not be equal, that is:
  $E_{RN} \neq E_{WN} \neq E_{BN}$
- Hence the neutral has shifted (Neutral Shift). This is demonstrated in the Figure B – 3 below.
- This phenomenon cannot be avoided in highly polluted areas.

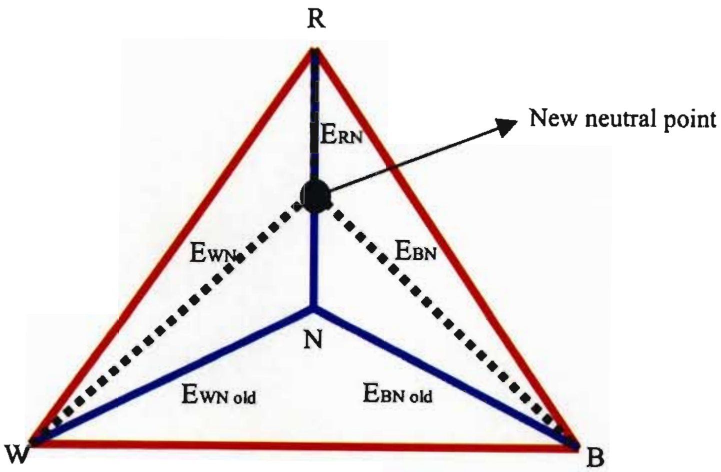

Figure B – 3: Phasor diagram illustrating the Neutral Shift.

APPENDIX C: Detailed wood pole leakage current recordings for August 1995.

Month	Date	Activity period	Maximum Current (mA)
August	06-Aug-95	00h10 - 01h00	0.4
		01h00 - 01h45	1.5
		01h45 - 02h00	4
		03h00 - 05h00	2.5
		05h30 - 06h00	2.8
		06h05 - 06h07	0.8
		06h30 - 07h00	1.2
		08h00 - 09h02	1.8
		10h05 - 11h00	3.2
	10-Aug-95	17h00 - 19h04	2.5
		19h45 - 20h00	1.8
		20h37 - 20h50	1.5
	11-Aug-95	01h54 - 06h45	0.8
	14-Aug-95	16h45 - 24h30	0.8
	15-Aug-95	00h01 - 07h00	2.6
		19h00 - 24h00	0.2
	16-Aug-95	04h30 - 05h23	3.6
		06h37 - 07h15	3.9
		08h00 - 08h19	0.7
		09h53 - 09h58	1
	18-Aug-95	00h01 - 09h00	0.3
		18h00 - 24h00	0.4
	19-Aug-95	00h01 - 09h00	0.3
		18h00 - 24h00	0.6
	20-Aug-95	00h01 - 10h00	0.8
	21-Aug-95	00h01 - 09h00	0.5
	22-Aug-95	Long periods	0.2
	23-Aug-95	Long periods	0.2
	24-Aug-95	Long periods	0.2
	25-Aug-95	Long periods	0.2
	26-Aug-95	Long periods	0.2
	27-Aug-95	Long periods	0.2
	28-Aug-95	Long periods	0.2

APPENDIX D: Detailed temperature (°C) recordings in Mtubatuba area for the month of August 1995.

Hrs Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	16	17	17	16	16	16	17	19	22	24	25	25	27	26	26	24	23	22	21	20	20	20	20	20
2	19	18	18	16	15	14	14	17	20	22	23	24	26	26	26	25	23	22	21	21	21	20	19	19
3	14	18	18	17	17	15	16	17	21	22	24	25	25	25	25	24	22	21	21	20	19	20	19	19
4	20	19	18	18	17	18	17	18	19	22	24	25	26	27	27	25	23	22	21	21	21	21	21	21
5	20	19	18	17	16	17	16	19	23	24	28	28	32	32	29	27	25	24	23	23	22	25	24	22
6	20	20	19	19	18	19	18	17	16	16	16	16	15	20	19	19	14	14	14	14	14	14	14	13
7	12	12	12	12	11	10	9	9	13	17	18	22	22	23	23	23	18	15	13	12	12	13	10	10
8	9	9	8	8	8	7	8	14	19	20	21	24	25	26	26	24	22	20	19	19	18	16	16	15
9	14	13	13	13	15	15	16	18	20	21	23	24	26	25	25	23	22	21	20	20	19	19	19	18
10	18	18	18	17	17	17	18	19	20	21	21	22	22	22	22	22	21	19	19	18	18	18	19	18
11	18	18	18	17	16	16	16	16	17	19	20	21	21	21	20	19	19	18	17	17	17	15	13	14
12	13	13	13	13	14	12	14	16	19	21	23	24	25	25	25	23	22	21	20	20	19	18	17	17
13	17	17	17	16	15	15	15	16	20	22	22	23	23	22	23	22	21	19	16	15	14	14	14	13
14	13	13	11	11	11	11	11	14	18	19	21	25	26	25	24	23	22	21	20	20	19	20	19	18
15	17	19	18	18	18	18	18	19	19	19	19	19	21	21	22	22	21	21	20	20	19	18	18	17
16	17	18	17	18	18	18	18	20	20	21	21	22	24	23	22	23	21	20	19	18	17	16	16	16
17	16	15	14	14	12	12	13	18	20	22	23	24	25	25	24	23	21	21	20	20	19	18	18	18
18	18	18	18	18	18	18	18	20	22	24	24	26	26	26	25	24	22	21	21	21	20	19	19	19
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21	18	17	18	18	18	19	20	21	22	24	24	26	26	26	26	24	23	22	21	22	22	22	21	21
22	21	20	20	19	18	17	19	19	20	22	25	26	25	25	24	23	22	21	21	20	19	18	16	16
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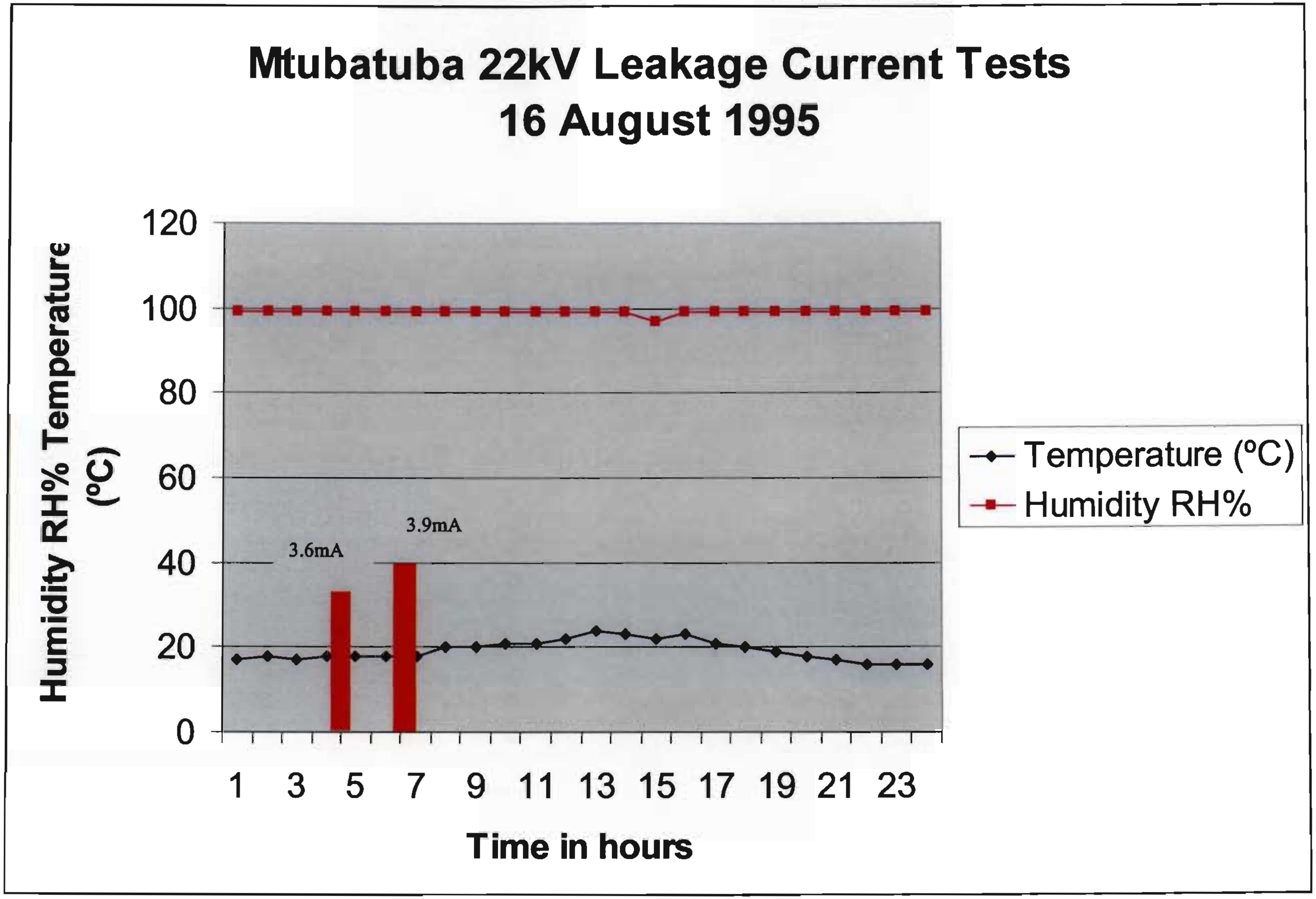
25	17	17	17	17	17	17	17	19	21	22	24	24	25	24	24	23	22	21	21	21	21	20	20	19
26	19	20	19	19	19	19	19	19	21	23	24	25	25	23	23	22	22	21	21	21	22	21	21	21
27	21	21	21	21	20	20	21	20	21	21	20	20	20	22	21	20	19	18	15	15	14	13	13	13
28	12	12	11	11	11	10	12	15	17	20	22	23	23	23	23	22	21	19	18	17	17	16	16	17
29	16	15	15	16	16	16	17	18	20	22	22	23	25	26	25	24	23	21	19	18	18	18	19	19
30	20	20	20	19	19	19	21	22	23	24	25	26	26	26	24	23	22	22	22	23	22	22	22	21
31	21	21	20	20	20	20	19	19	18	18	19	20	21	21	21	21	20	18	16	16	16	16	16	15

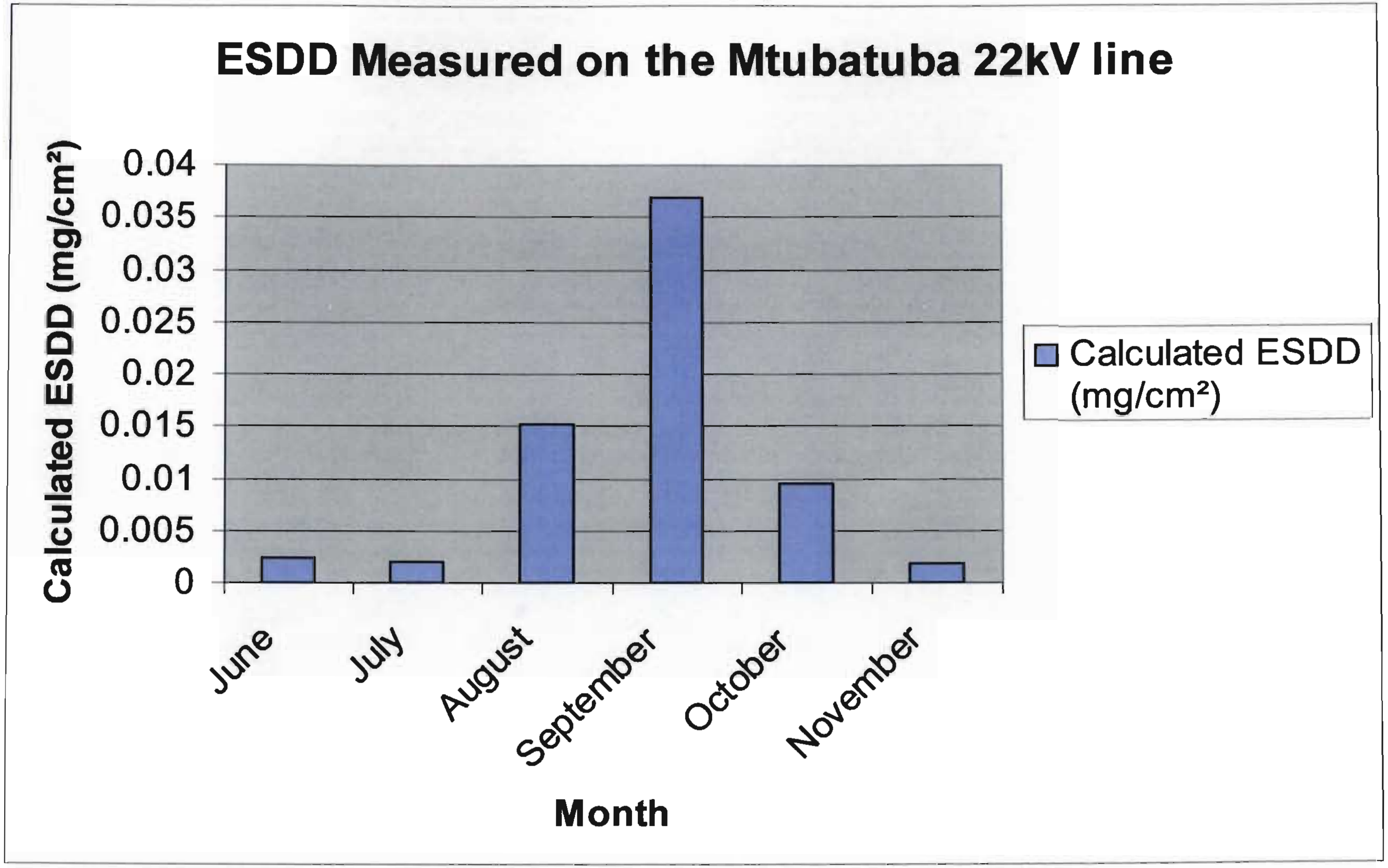
APPENDIX E: Detailed Relative Humidity (%) recordings in Mtubatuba area for the month of August 1995.

Hrs / Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	99	99	99	99	99	99	99	99	95	77	64	56	52	48	48	58	71	82	84	88	88	90	92	94
2	94	94	96	98	98	98	98	96	88	79	73	62	57	53	53	60	69	82	80	76	77	77	80	82
3	79	73	69	69	73	67	71	69	64	39	36	29	26	29	44	50	47	52	56	63	82	81	85	99
4	95	93	93	79	83	89	95	91	75	50	44	36	31	29	36	39	52	75	85	89	83	75	74	72
5	66	77	85	83	81	72	76	68	40	39	22	20	19	22	25	37	45	54	56	47	51	54	91	99
6	99	99	99	99	99	99	99	99	99	99	99	99	99	91	81	85	87	99	99	99	99	99	99	99
7	99	99	99	99	91	87	87	83	68	57	45	39	28	23	25	29	40	66	72	83	87	81	83	77
8	77	81	81	81	81	87	97	85	78	54	47	32	34	28	29	40	49	66	77	81	77	90	93	97
9	99	99	99	99	99	99	99	95	81	54	45	44	39	34	36	59	78	95	99	99	99	99	99	99
10	99	99	99	99	99	99	99	99	99	95	85	77	77	68	66	71	79	99	99	99	99	99	99	99
11	99	99	99	99	99	99	99	99	99	99	85	52	47	52	54	59	75	83	87	91	91	99	99	99
12	99	99	99	99	99	99	93	81	70	63	54	50	44	44	47	74	91	95	97	97	93	87	89	90
13	95	99	99	99	99	99	99	97	87	79	76	66	65	70	70	65	68	79	83	95	99	99	99	99
14	99	99	99	99	99	99	99	99	99	99	91	77	68	72	63	72	99	99	99	99	99	99	99	99
15	99	99	99	99	99	99	99	99	99	99	99	99	99	91	89	93	99	99	99	99	99	99	99	99
16	99	99	99	99	99	99	99	99	99	99	99	99	99	99	97	99	99	99	99	99	99	99	99	99
17	99	99	99	99	99	99	99	99	99	99	87	63	63	57	61	77	85	99	99	99	99	99	99	99
18	99	99	99	99	99	99	99	99	97	74	66	57	52	50	52	74	83	99	99	99	99	99	99	99
19	99	99	99	99	99	99	99	99	99	95	85	68	61	59	68	79	85	99	99	99	99	99	99	99
20	99	99	99	99	99	99	99	99	99	91	75	66	59	54	54	64	75	99	99	99	99	99	99	99
21	99	99	99	99	99	99	99	99	99	99	97	79	70	56	66	90	81	99	99	99	99	99	99	99
22	99	99	99	99	97	89	76	68	65	57	57	52	57	59	57	64	61	72	76	77	83	89	91	91
23	99	99	99	99	99	99	99	99	85	77	68	61	63	61	70	74	85	89	95	97	97	97	99	99
24	99	99	99	99	99	99	99	99	87	72	70	68	70	70	72	77	87	97	98	99	99	99	99	99
25	99	99	99	99	99	99	99	99	99	93	75	65	61	57	63	72	99	99	99	99	99	99	99	99
26	99	99	99	99	99	99	99	99	93	56	52	50	50	50	50	79	91	99	99	99	99	99	99	99
27	99	99	99	99	99	99	99	99	99	99	99	91	64	61	59	64	68	79	87	91	99	99	99	99
28	99	99	99	99	99	99	99	99	89	63	59	57	56	59	58	63	75	99	99	99	99	99	99	99
29	99	99	99	99	99	99	99	99	99	87	72	63	57	48	51	68	81	99	99	99	99	99	99	99
30	99	99	99	99	99	99	99	99	99	99	70	65	57	52	51	57	77	91	99	99	99	99	99	99
31	99	99	99	99	99	99	99	99	99															

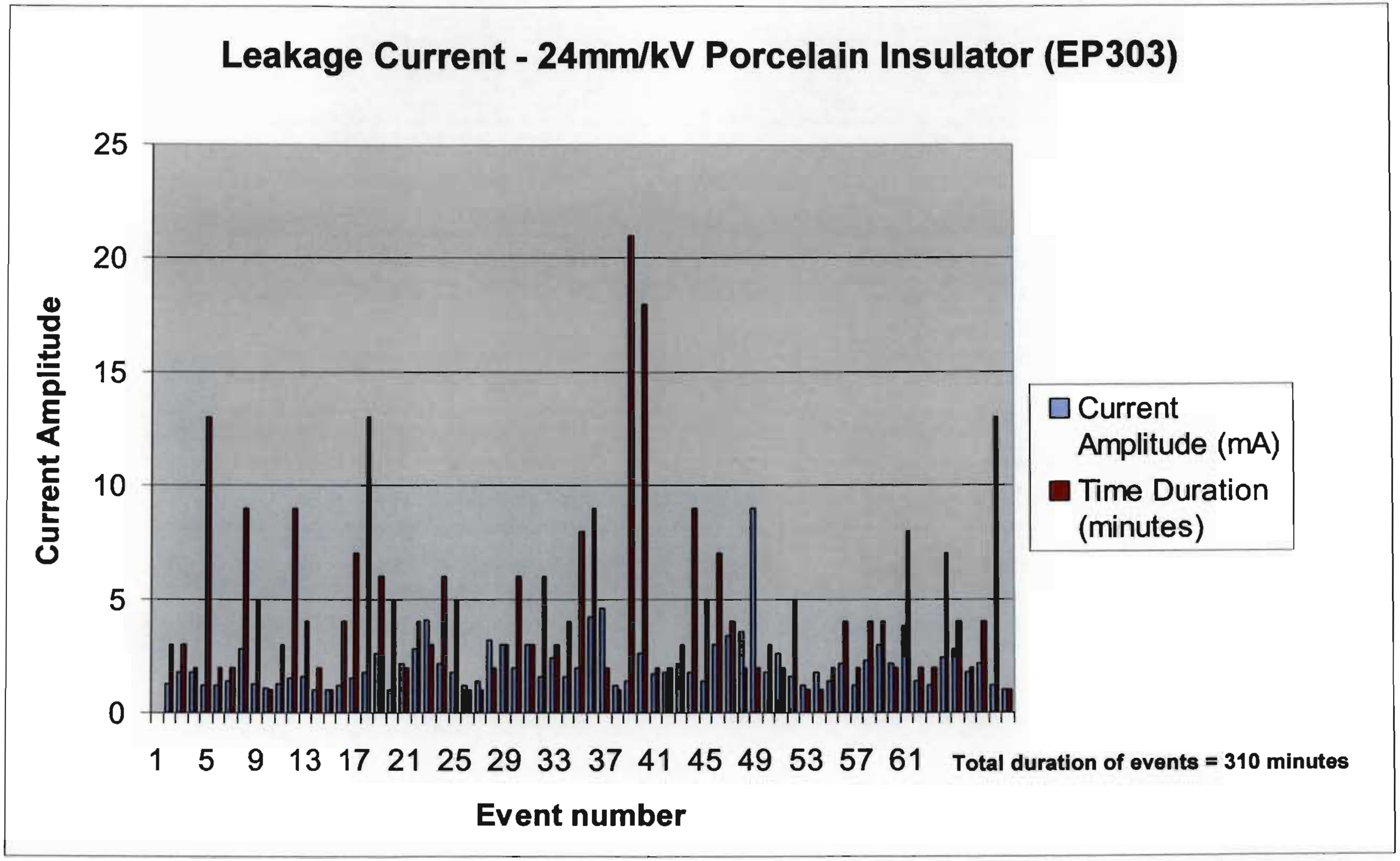
APPENDIX F: Graph of Temperature and Relative Humidity (RH %) versus Time for August 1995



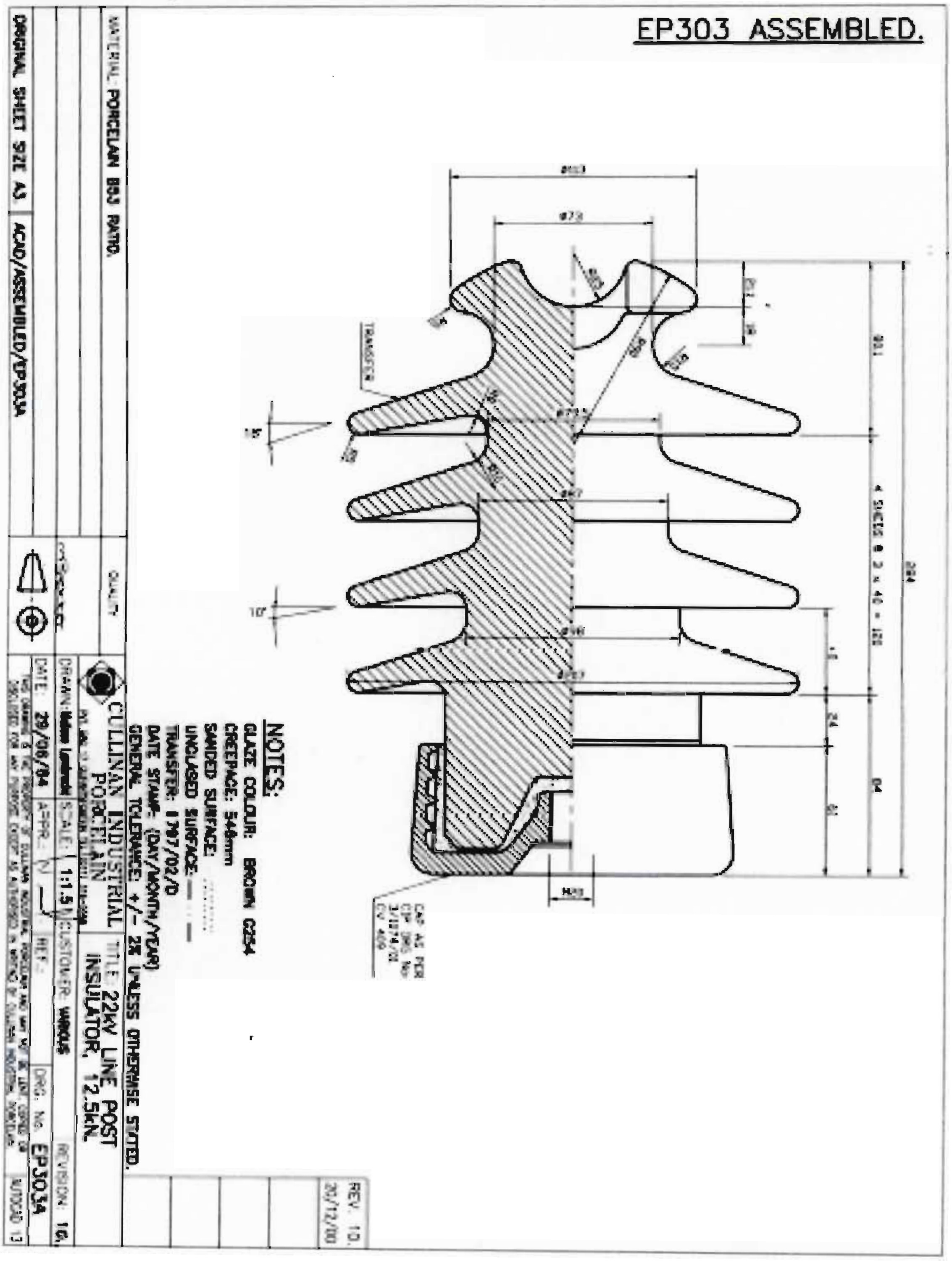
APPENDIX G: Equivalent Salt Density Deposit (ESDD) pollution level graph.



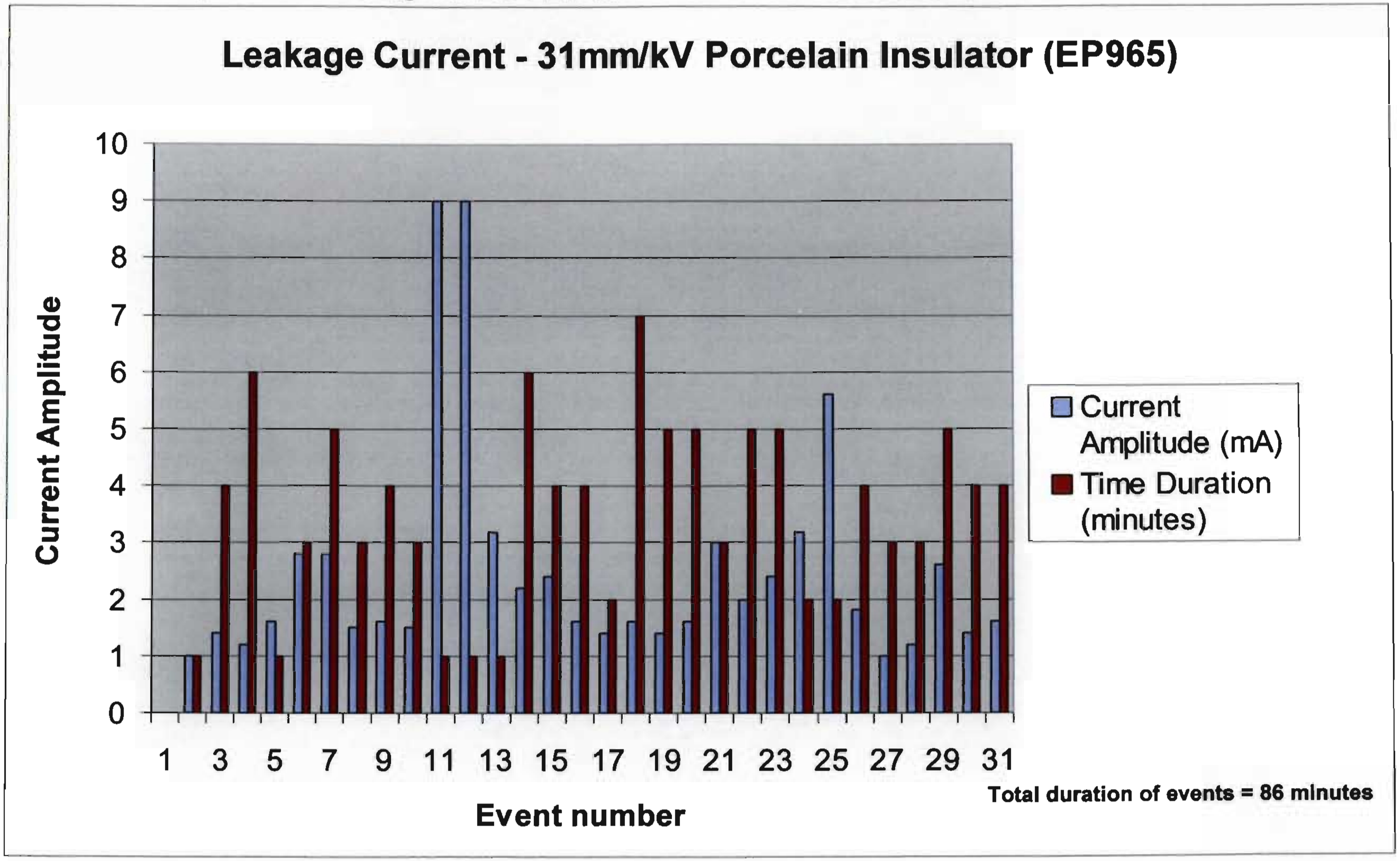
APPENDIX H: Graph of results of leakage currents on the EP303 Insulator between June 1996 and November 1996.



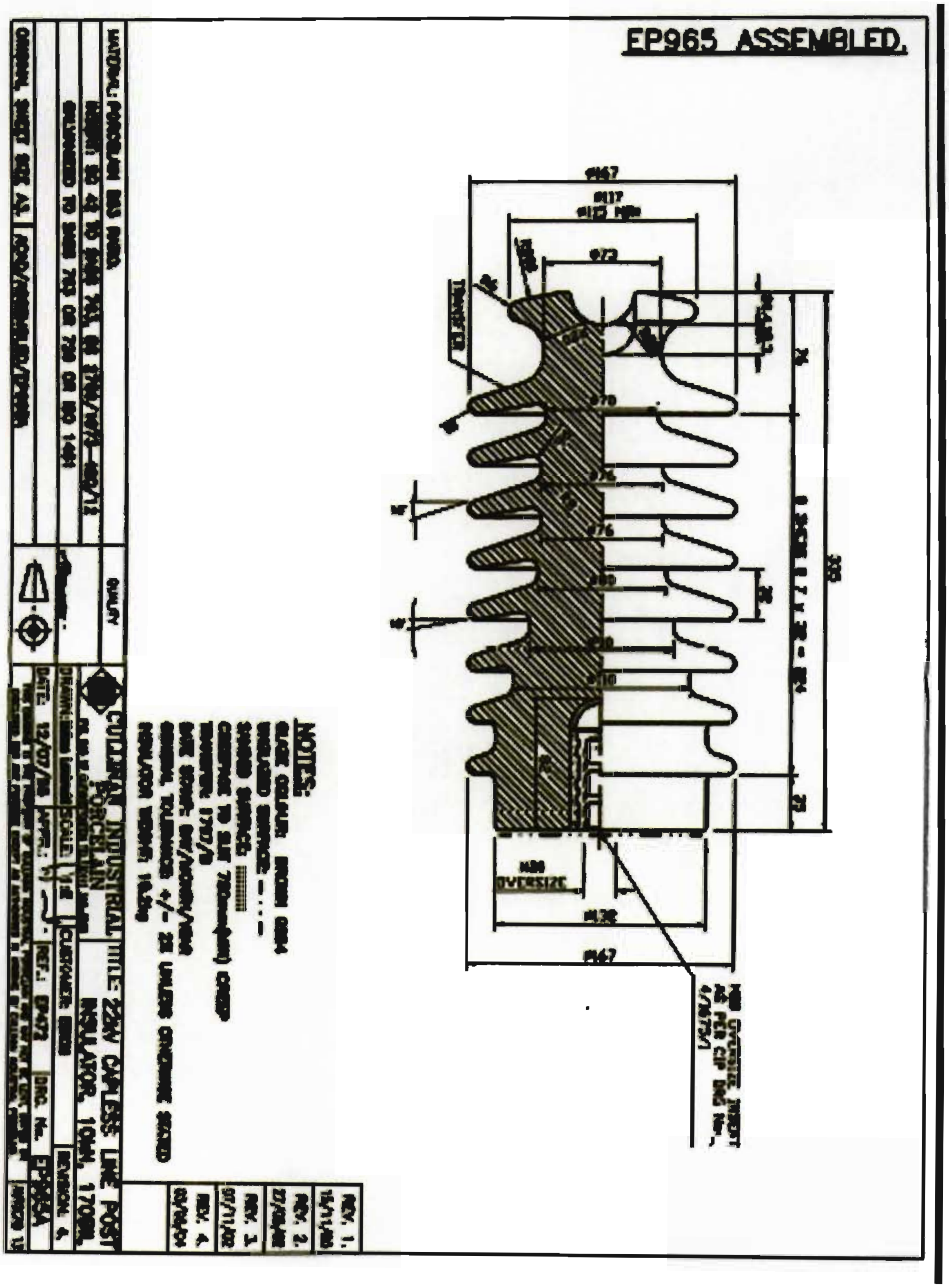
APPENDIX I: Specification for Insulator EP303



APPENDIX J: Graph of results of leakage currents on the EP965 Insulator between June 1996 and November 1996.



APPENDIX K: Specification for Insulator EP965



APPENDIX L: Calculation of Electric Field inside the cross arm.

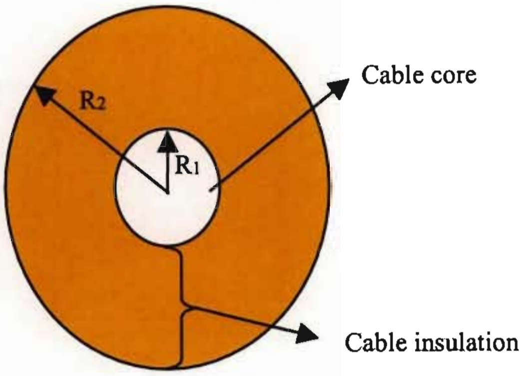


Figure L - 1: Co-axial geometry of a cable

From basic High Voltage Engineering theory, it can be shown that the highest electric field E occurs at the maximum value of R_1, where R_1 = outer radius of the cable core. R_2 = radius of cable. That is:

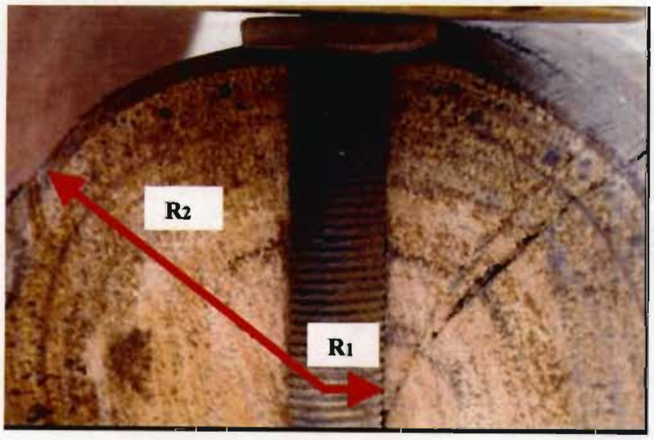
$$E_{max} = \frac{V}{R_1 \ln(R_2/R_1)}$$

Similarly, in the case of the cross arm R_1 = radius of spindle and R_2 = radius of the cross arm. Once again the highest electric field E will occur at the threads of the spindle. Eskom Distribution uses M20 spindles / threaded rods to mount medium voltage (22kV) insulators. Hence R_1 = 10mm. Also, 160mm pole top diameter cross arms are predominantly used on most structures. Hence R_2 = 80mm. As per 4.6.3 the voltage measured between the spindle and bottom end of the porcelain insulator surface was 300V. Hence applied voltage V = 300V. Therefore:

$$E_{max} = \frac{300}{10\ln(80/10)}$$

$$= \underline{14.43\text{Vmm}^{-1}}$$

This is an astonishingly high figure which could easily lead to sparking resulting in the cavities found between the spindle / threaded rod and the wood.



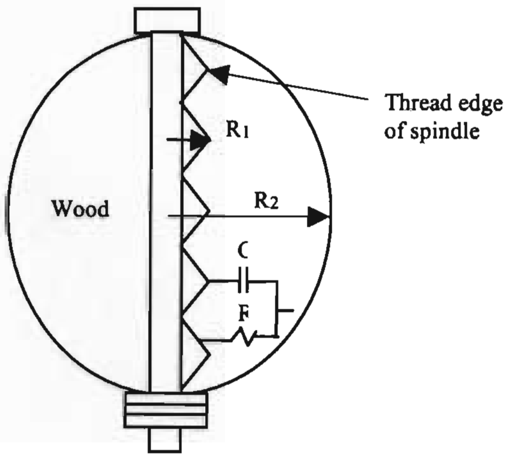


Figure L - 2: Cross section of the wood cross arm with spindle

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