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JOHANNESBURG

THE EARTHING OF LARGE MOBILE ELECTRICALLY DRIVEN MACHINERY IN A STRIP MINING ENVIRONMENT

PROJECT REPORT SUBMITTED AS PART REQUIREMENT
FOR THE DEGREE OF M.Sc. (ENG.) IN THE
BRANCH OF ELECTRICAL ENGINEERING

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ABSTRACT

This report investigates the current methods of earthing mobile electrically driven machinery in a strip mining environment. Attention is paid to the protection of people in the vicinity of mobile equipment from lightning and power frequency overvoltages, and recommendations are made in this regard. The effects of current flow on the human body are discussed, and limitations on power frequency and lightning touch potentials are set. An earthing arrangement is proposed and analysed. It is expected that this system will result in lower and more consistent values of power frequency and surge impedance to earth than the system presently in use.

TABLE OF CONTENTS

CHAPTER 1
INTRODUCTION

This project was undertaken in order to address the following areas of concern to operators of mobile electrically driven machinery in a strip mining environment:

a) A number of equipment failures, particularly to skid mounted transformers, have been experienced during previous summer seasons. The majority of these failures have been due to lightning surges. It was felt that the earthing arrangement currently employed could be partly responsible for this state of affairs. The need to critically examine the practicality and technical integrity of the present earthing system was therefore apparent.

b) Current opinion at the time of initiation of this project was that physical separation of the 33kV and 6,6kV earthing systems would prevent potentials hazardous to people occuring on the dragline and distribution skid due to elevations in the potential of the transformer skid and 33kV earthing system. A need existed to test the validity of this assumption, as a number of fatalities have occured in the United States of America due to electrocution by touch potentials present on mobile machine frames (11).

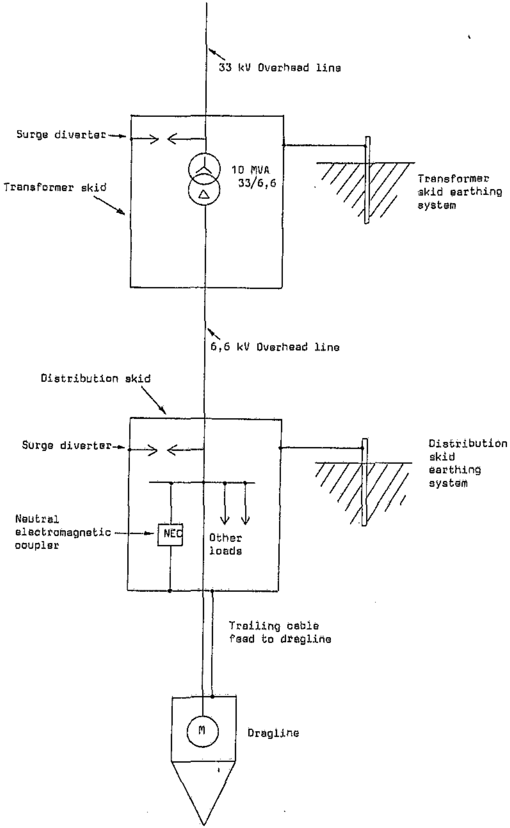
c) A need existed to formulate practical measures which should be taken to protect people working on mobile equipment from dangerous touch potentials, whether these be caused by power frequency faults or by lightning discharges.

The question of the earthing of mobile electrically driven machinery is essentially one of safety to personnel. The machinery is fed via cables and allows free access to personnel for maintenance and operation. Any potential which may appear between the machine and the surrounding ground which may be bridged by a person must ideally therefore be strictly controlled within well defined safe limits. The problem is magnified by the fact that mobile electrical machinery is often fed from power lines of up to 33kV, via mobile substations. Consequently such systems are susceptible to lightning overvoltages,requiring the discharge to earth of appreciable currents.

For the purpose of this report, the specific example of an electrically operated cable fed dragline in a strip mining operation is considered. A currently accepted method of supplying power to such a machine is shown diagrammatically in figure 1.1.

Figure 1.1

Diagrammatic layout of the power supply to a dragline



An essential feature of this design is the manner in which the 33kV and 6,6kV ea,thing systems are separated. The reason for this is as follows.

As it is impractical to provide an earth electrode in the vicinity of the dragline, the dragline frame is connected via the flexible trailing cable earth conductor to the distribution skid frame, and thus to earth via the 6,6kV earthing electrode system. Any rise in potential experienced by the distribution skid will therefore be transmitted to the dragline, which will then rise to that potential above the surrounding earth.

Present practice is to employ a neutral earthing resistor on the 6,6kV distribution system which limits the power frequency fault current to 25A. The potential of the distribution skid would also rise when a potential surge of sufficient magnitude occurred on the 6,6kV lines to enable the surge diverter to operate. This potential is a function of the diverter discharge current, the surge impedance of the 6,6kV earthing electrode system, and the ionisation characteristics of the soil medium around the electrodes, and could be appreciable. However, as this section of line is only about 15m long, current opinion of mine operators is that lightning surges to this line, especially those caused by direct lightning strikes, should be relatively rare occurrences.

The transformer skid experiences potential rises by similar mechanisms to those applicable to the distribution skid. However, in the case of a power frequency fault on the 33kV system, the total prospective fault current is largely determined by the earthing arrangement of the supply authorities transformer neutral point, over which the consumer has little control. It is also expected that lightning induced surges will occur frequently on the 33kV side of the transformer.

The transformer and distribution skids and their respective earthing systems are therefore physically separated, in order to prevent as far as possible, rises in potential of the transformer skid being reflected onto the distribution skid and thereby to the dragline frame. This aspect of the present design is discussed in more detail in chapter 3.

CHAPTER 2
DETERMINATION OF MAXIMUM PERMISSABLE POTENTIAL ACROSS THE HUMAN BODY

2.1 INTRODUCTION

Essential to the design of an earthing system for a mobile electrical machine is the determination of the maximum potential to which the human body may be subjected without injurous effect. Although some work has been done on this subject, the results obtained have been largely subjective, as testing can obviously not be carried out on living people. A conservative approach is therefore indicated.

The factors which determine the seriousness of electric shock are:

a) Body resistance and
b) The current imposed on the body and the length of time for which this current is imposed (10).

2.2 BODY RESISTANCE

The resistance of the human body varies with the potential imposed (1). Table 2.1 below gives the relationship between body resistance and touch potential for a current flow from hand to hand or hand to foot (1). It is assumed that the conductor is gripped and that a normal amount of perspiration is present on the skin. This relationship is graphed as curve A on graph 2.1.

TABLE 2.1 VARIATION OF BODY RESISTANCE WITH TOUCH POTENTIAL

Touch Potential(volts)	Body Resistance (Ohms)
25	2 500
50	2 000
250	1 000
Asymptotic value	650

Tests done on human corpses with the epidermis intact gave the relationship between body resistance and touch potential shown in Table 2.2 (2).

TABLE 2.2 VARIATION OF BODY RESISTANCE WITH TOUCH POTENTIAL - HUMAN CORPSES WITH EPIDERMIS INTACT

Touch Potential (volts)	Body Resistance (Ohms)
30	100 000
100	40 000
200	2 000
1 000	600

A portion of the relationship shown in table 2.2 is graphed as curve B is on graph 2.1. However, when contact was made below the epidermis of human corpses, body resistance was found to be constant at 600 ohms at all voltages (2). This relationship is shown as curve C on graph 2.1.

The internal resistance of the human body is generally accepted to be no greater than 1000 ohms (2,10). This condition is graphed as curve D on graph 2.1.

Curves C and D of graph 2.1 correlate well with curve A for contact potentials of above about 250 volts. Below this level, however,curves C and D ignore the accepted phenomenon of increasing body resistance with decreasing touch potential.

It is proposed that the variation of body resistance with touch potential as depicted in curve A of graph 2.1 be adopted. Curve A is more conservative than the measured results shown by curve B, but is not unacceptably conservative, as cognizance is still taken of the increase in body resistance with decreasing touch potential.

2.3 CURRENT TIME RELATIONSHIP

Graph 2.2 shows the relationship between power frequency current through the body, the time for which the current flows and the likely effect of the current flow. This graph is reproduced from I.E.C. Publication 479 and is based on the following assumptions:

a) Body mass of not less than 50kg.

b) Current flows from hand to foot through the heart.

Assuming a maximum power frequency fault clearance time of 500ms, graph 2.2 predicts the following human body reactions:

Zone 1	$I \leqslant 0,5$mA	No reaction effect.
Zone 2	0,5mA $< I \leqslant$ 35mA	No pathophysiologically dangerous effect.
Zone 3	35mA $< I \leqslant$ 110mA	Usually no danger of fibrillation.
Zone 4	110mA $< I \leqslant$ 500mA	Up to 50% danger of fibrillation.
Zone 5	500mA $< I$	Greater than 50% [illegible] of fibrillation.

A second important criterion in determining the allowable current to which a body may be subjected is the let go current, this being the value of current above which voluntary control over muscle action is lost. The experimental determination of let go currents is quoted by Smith (2). Tests were conducted on 134 men and 28 women. The average value of let go current was established as 15,87mA for men and 10,5mA for women, with a calculated 99,5% of men being able to release a gripped conductor at a current level of 8,8mA.

It is recommended that the power frequency current flow be limited to 50mA. The selection of this value of current is justified for the following reasons:

a) Only adult males will be subject to electric shock in a strip mining operation.

b) Protection will normally operate in a shorter time than 500 ms, this being the expected time for backup protection to operate should the primary protection fail to clear the fault.

c) The relationship between fibrillating current and shock duration can be represented by the expression (9):

$$I = \frac{116}{\sqrt{t}}$$ where I = R.M.S. current, mA
t = shock duration, s.

For a shock duration of 500ms the fibrillating current would, from the above expression, be 164mA. The value of 50mA chosen is therefore conservative.

Curve E on graph 2.1 is a plot of $V_{touch} = IR_{body}$ with I = 50mA. The intersection of curves E and A gives the maximum permitted touch potential of 80V for an alternating current of 50mA imposed for 500ms.

This result compares favourably with statutory maximum permissable touch potentials in other countries. In Europe the limit varies from 24 volts in France to 50 volts in other countries (2). In the U.S.A. strip mines, touch potentials are limited to 100 volts (11).

The foregoing discussion dealt with permissible touch potential when a power frequency current of 500ms duration flows through the body. When however, a person is subjected to a lightning discharge, the duration of current flow is about 8,3 ms (4). This corresponds to a peak current magnitude of (9).

$$I_{peak} = \sqrt{2}\,\frac{116}{\sqrt{0,0083}}$$

$$= 1,8 \text{ Amps}$$

If a standing person receives a direct lightning strike to his head, external flashover between head and feet will occur when the potential across the boc reaches approximately 1000kV. The potential difference accross the body will then collapse to about 4kV (4,10). Such high imposed voltages therefore lead to the conclusion that a body resistance of between 500 ohms and 1000 ohms will obtain under lightnin te conditions (see Graph 2.1) (4,10).

The maximum permissible touch potential under lightning conditions can therefore be conservatively limited to:

$$V_{touch} = I\,R_{body}$$

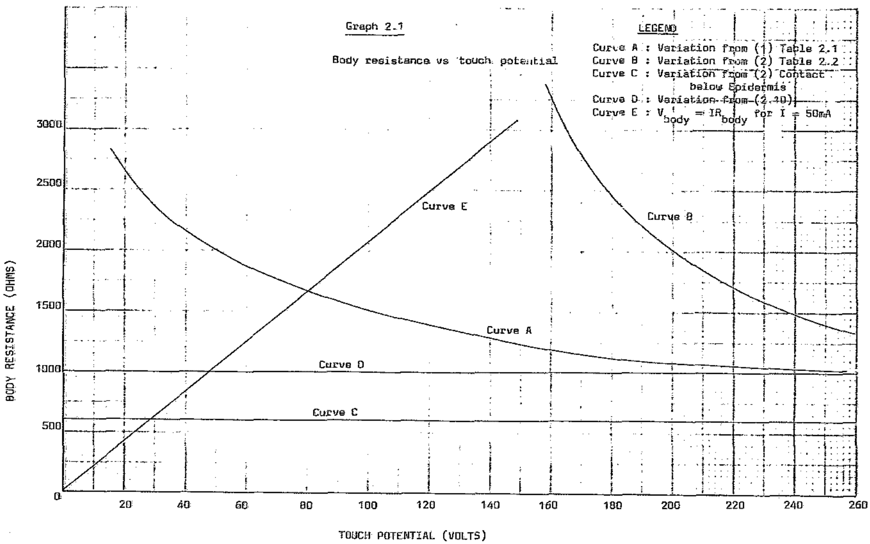
$$= 1,8 \times 500$$

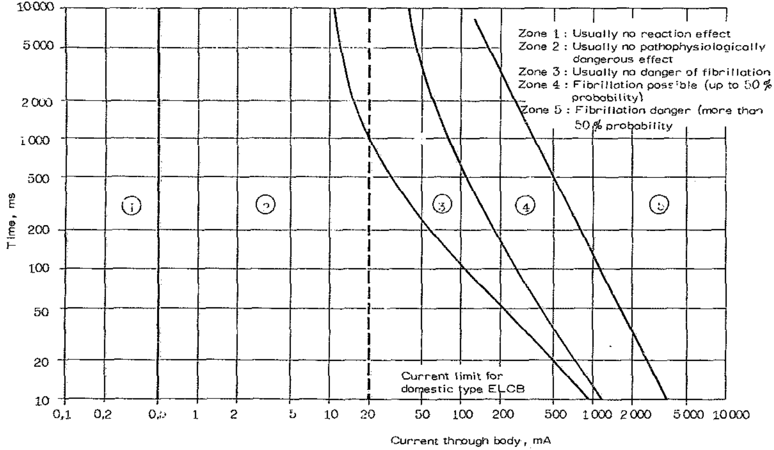
$$= \underline{900 \text{ volts}}$$

It should be noted that this limitation placed on touch potential applies specifically to the case of a single stroke flash of 8,3 ms duration. It is recognised that the allowable touch potential may vary when a person is exposed to a multiple stroke flash. Multiple stroke flashes have a mean duration of 148 ms and a median duration . 67 ms (13).

Fifty percent of time intervals between strokes exceed 35ms while 90% exceed 10ms and 1,5% exceed 300ms (13). About 20% of lightning flashes have 6 or more component strokes (13).

A more rigorous determination of the maximum allowable touch potential under lightning stroke conditions, which made allowance for the effect of multiple stroke flashes could result in a decrease in the permissible limit of 900 volts previously determined. Any such reduction would not however, have any effect on the conclusions ultimately drawn in this report.


Graph 2.1
Body resistance vs touch potential
LEGEND
Curve A : Variation from (1) Table 2.1
Curve B : Variation from (2) Table 2.2
Curve C : Variation from (2) Contact below Epidermis
Curve D : Variation from (2.10)
Curve E : $V_{body} = IR_{body}$ for I = 50mA
Curve A
Curve B
Curve C
Curve D
Curve E
BODY RESISTANCE (OHMS)
TOUCH POTENTIAL (VOLTS)
0
500
1000
1500
2000
2500
3000
20
40
60
80
100
120
140
160
180
200
220
240
260



- Human Body Reactions to Body Current and Time Duration

<u>GRAPH 2.2</u>

Reproduced from IEC Publication 479

CHAPTER 3

OVERVOLTAGES TO WHICH PERSONNEL MAY BE EXPOSED.

3.1. OVERVOLTAGES CAUSED BY POWER FREQUENCY FAULTS

A power frequency fault to earth on a dragline will cause current to flow through the fault back to the neutral of the point of supply.

Present practice is to provide an earth return path to the secondary side of the 33kV/6,6kV transformer via an earth core in the cable supplying the dragline. The prospective earth fault current is limited to 25 Amps by a resistor placed in the neutral of the 6,6 kv supply. This arrangement is shown diagrammatically in figure 3.1, the arrows thereon showing the path of earth fault current flow, for an earth fault on the item of mobile equipment.

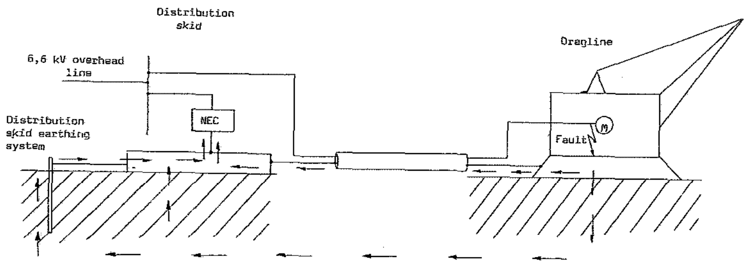
The maximum potential to which the dragline frame will rise is the product of the maximum fault current and the impedance between the point of fault and the neutral of the point of supply. The earth return path impedance will be no greater than 0,38 - j 0,13 ohms per kilometre (12). Assuming a maximum cable length of 6 kilometres, the maximum touch potential will be:

$$V = I\ Z$$
$$= 25 \times 6\ (038 - j\ 0,13)$$
$$= 57 - j\ 19,5 \text{ volts}$$

$$|V| = 60,24 \text{ volts}$$

Figure 3.1

Diagrammatic representation of the flow of fault current for a phase to earth fault on a dragline



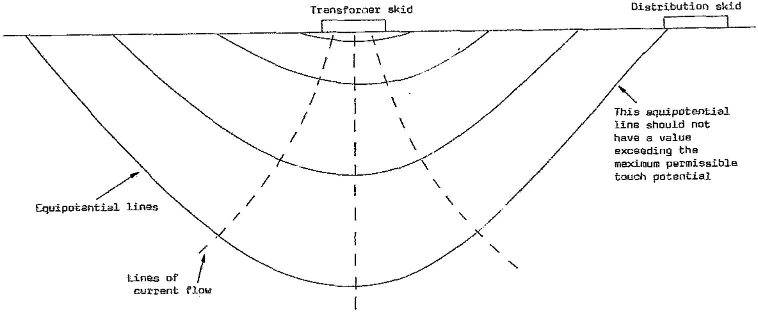
3.2 OVERVOLTAGES CAUSED BY LIGHTNING

When lightning strikes an item of mobile equipment, the stroke current flows through all available paths to earth. The mobile equipment frame will experience a maximum rise in potential equal to the product of the peak stroke current and the surge impedance between the frame and the mass of the earth. The peak current amplitude of lightning can be taken as having a median value of 34kA, with a probability of exceeding 100 kA of 2,5% for structures having a height of less than 60m (7).

Should a lightning discharge occur through the transformer skid, either by a direct strike to the skid or by a surge diverter discharge, equipotential lines will be established in the ground around the skid, as the discharge current flows from the source (transformer skid) to the sink (earth). This situation is shown diagrammatically in Figure 3.2. It i[illegible]esirable to place the distribution skid at such a point [illegible] equipotential line intersected by the distribution sk[illegible]ng arrangement does not have a value exceeding the permissib[illegible]uch potential. The location of this point, for any specific value of peak current and earth electrode system surge impedance, is a function of the shape of the resistance versus distance curve around the distribution skid.

Figure 3.2

Diagrammatic representation of the establishment of equipotential lines *when current is discharged through the* transformer skid



CHAPTER 4

RESISTANCE AND RESISTIVITY MEASUREMENTS

4.1 INTRODUCTION

In order to design an earth electrode system it is necessary that design paramaters such as earth resistivity be known. The author took measurements of earth resistivity and of the resistance to earth of various items of mobile equipment to earth on strip mines. In addition, earth resistivity surveys have been carried out on some of the mines. The results of these surveys, together with the measurements taken, provided the basis for certain assumptions to be made in regard to the design paramaters which should be adopted.

4.2 METHOD OF MEASUREMENT

4.2.1 Soil Resistivity

The four terminal Wenner array method was used for measuring earth resistivity (3). In this method, four electrodes are planted into the ground, uniformly spaced in a straight line. It can be shown that : (3)

$$\rho = 2aR\pi$$

where a = spacing between electrodes (metres)

R = measured resistance (ohms)

ρ = resistivity (ohm metres)

Values of resistivity were obtained for various electrode spacings at each resistivity measurement site. If resistivity is plotted against electrode spacing a so called "depth curve" is obtained. The interpretation of such curves is the subject of much controversy (1,3). For the purposes of this report the variation in resistivity with electrode spacing was interpreted as giving no more than a very rough indication of the variation of resistivity with depth. It was felt that lack of comprehensive geological information at the measurement sites precluded any more definitive conclusions being drawn.

4.2.2 Resistance

Measurements were made on various items of mobile equipment in order to determine:

a) The value of resistance to earth and
b) the approximate shape of the resistance versus distance curve in the vicinity of the electrode under consideration.

Measurements were made using the "Fall of Potential" method (3). In this method current is caused to flow through the earth between two electrodes, one of these electrodes being the earth electrode under consideration, and the other being an auxillary electrode inserted in the ground some distance from the first. A so called "potential electrode" is then placed along the line joining the two current electrodes. The potential drop between the electrode under test and the potential electrode is then measured and as the magnitude of the current flow causing this voltage drop is known, the potential measurement is converted to a reading of resistance between the electrode under test and the potential electrode.

Resistance measurements were made for various positions of the potential electrode, and a curve of resistance versus distance away from the electrode under test was thereby obtained.

It is important when making resistance measurements to ensure that the resistance volumes of the electrode under test and the auxilliary current electrode do not overlap significantly. The degree of overlap of these two resistance volumes can be appraised from the slope of the curve at its flattest point, which occurs approximately midway between the two electrodes. The flatter the curve is at this point the greater is the degree of separation between the two resistance volumes. It should be noted that it is not theoretically possible to obtain a perfectly flat curve at this point.

The value of the resistance to earth of the electrode under test is given by the resistance value read from the resistance versus distance curve at a distance from the electrode under test to the potential electrode equal to 61,8% of the distance between the two current electrodes (3). The accuracy of the value of the resistance

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The value of the resistance to earth of the electrode under test is given by the resistance value read from the resistance versus distance curve at a distance from the electrode under test to the potential electrode equal to 61,8% of the distance between the two current electrodes (3). The accuracy of the value of the resistance to earth thus obtained is a function of the flatness of the curve at the midpoint. This is a function of the distance between the two current electrodes. Accuracy therefore increases with distance between the two current electrodes.

Wherever practically possible, the distance between the two current electrodes was made to be greater than 5 times the largest dimension of the electrode under test. Where it was not practical to achieve this degree of separation, the resulting resistance versus distance curve was examined to ensure that the resistances at 51% and 67% of the distance between the two current electrodes did not vary by more than 5% from the resistance at 61,8%. This degree of accuracy was considered acceptable for the following reasons:

a) The value of resistance to earth would vary greatly in the normal course of events due to factors over which no control could be exercised such as rainfall, which would change the resistivity of the soil over an appreciable range.

b) The shape of the resistance versus distance curve in the vicinity of the earth electrode was of great interest. This shape, especially close to the earth electrode, is largely independant of the limiting value of the resistance to earth, and is independant of the resistivity around the earth electrode, assuming that the soil resistivity is uniform throughout the electrode resistance volume.

4.3 DISCUSSION

Although a wide variation in soil resistivity was encountered during field measurements, it was decided that a single value of resistivity should be used for the design of earth electrode systems in all cases. This approach would obviously lead to a single recommended earth electrode design. The disadvantage of this approach is that in installing an earthing electrode system at any particular location advantage would not be taken of any value of soil resistivity at that location which may be significantly lower than the overall resistivity value assumed. This would result in an unnecessarily expensive system being installed. The advantage of such an approach is that a single earthing arrangement would obtain on all strip mines in the group. This would facilitate monitoring by management of the correct installation of earthing systems and make acceptable design of the electrode system independant of soil resistivity appraisals at individual locations.

Data from resistivity measurements have been taken from three sources:

a) Work carried out by J E Pontin (Pty.) Ltd. on Duvha Mine on I March 1983 and 3rd March 1983. The moisture content of the soil during these tests is not known. The results of this work are summarised in Appendix 1.

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b) Work carried out by Pontech (Pty.) Ltd. on Rietspruit Mine on 20 July 1983. The soil was described as "dry" in the test report. The results of this work are summarised in Appendix 2.

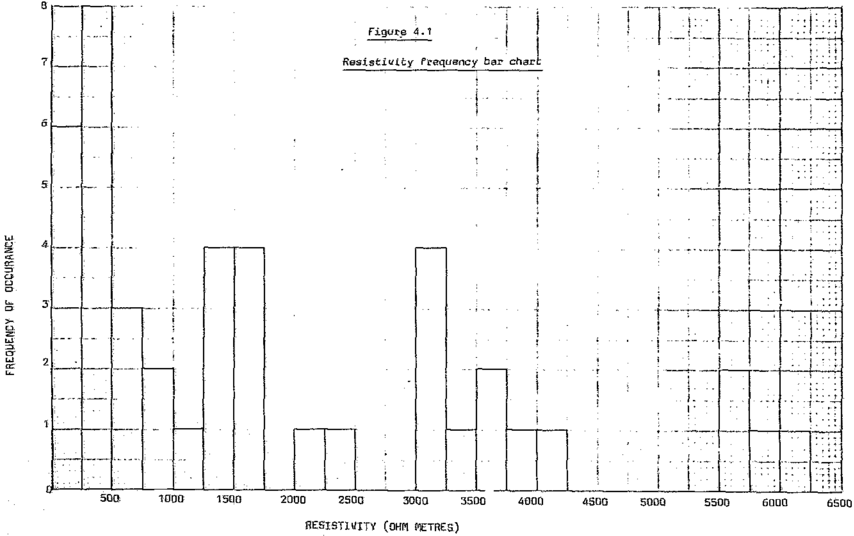
c) Work carried out by the author. Some results of this work are given in Appendix 3.

In order to gauge the variation of earth resistivity a frequency bar chart of resistivity was drawn up and is shown in figure 4.1. In order that a conservative although not unrealistic assumption of resistivity be drawn it was assumed that the resistivity measured at an electrode spacing of 2m obtained at all depths in the soil.

It was decided, after examination of figure 4.1, that for the purposes of design, the soil resistivity should be taken as 3 000 ohm metres. This value would apply to dry soil at all locations under consideration. Should an earthing electrode system designed for 3000 ohm metre soil be installed in soil of 6008 ohm metres resistivity (the highest measurement recorded), the resistance to earth of the electrode system would be approximately twice that of the system installed in 3000 ohm metre soil. This is considered acceptable as only 10% of readings were above 4250 ohm metre resistivity. It is much more likely that the electrode system will have a lower resistance than that based on a 3000 ohm metre resistivity, as 66% of resistivity readings were below this value.

Figure 4.1

Resistivity frequency bar chart



CHAPTER 5
THE EARTH ELECTRODE SYSTEM

5.1 PRESENT EARTHING SYSTEM

The earthing practice presently being followed on some strip mines has been formulated to overcome the two recognised major problems, namely;

a) The high soil resistivities which commonly prevail and
b) The desirability of separating the 33 kV and the 6,6kV earthing systems.

The problem of high soil resistivity is addressed by specifying an electrode depth of between 8m and 12m, depending on location. This is done in an attempt to utilise lower soil resistivity normally found at greater depths below the surface. An attempt is made to further reduce resistance to earth by installing four such electrodes in parallel. Surge impedance is reduced by connecting these four electrodes in the form of a "crows foot".

The problem of separation of the transformer and distribution skid earthing systems is addressed by installing the two earthing systems approximately 50m apart. The earthing systems are then connected to their respective skids by means of insulated cables. The skids can be as close together as 10m. A typical earthing arrangement is shown in figure 5.1

The present earthing system, although based largely on judgement rather than on a more rigorous engineering appraisal of the problem, represents a significant advance on previous earthing arrangements generally employed in the industry.

The present system does however, suffer from a number of practical and technical drawbacks. These are as follows:

a) The four vertical rods are placed in the form of a square, with a side dimension of about 5 metres. There is therefore considerable overlap of the resistance volumes of the individual rods with each other. The potential for lowering the earthing resistance obtainable by using four rods in parallel is therefore not fully utilised.

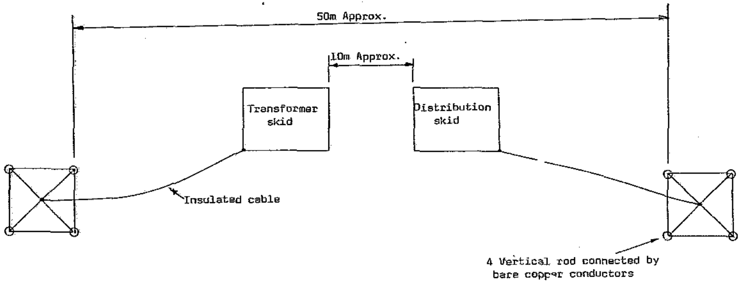
b) Drill rigs, normally under the control of the Production Department, are required to drill the deep holes necessary for the insertion of the earth electrodes. Moving these drill rigs to the skid sites is a time consuming exercise and lowers the productive utilisation of what is essentially a production machine. As a consequence , power has been applied to skids before the necessary earthing system has been installed. When this occurs, the Electrical Department normally installs a temporary arrangement of four 1 metre long stakes in a crows foot pattern.

c) The four vertical electrodes are interconnected by bare copper conductors. These conductors are seldom buried. As the resistance to earth of the earthing system is directly proportional to the area of conductor in contact with the soil the potential of the interconnecting conductors for further lowering the resistance of the earthing system to earth is not utilised.

d) In determining the required physical separation of the transformer and distribution earthing systems, the resistance to earth of the skids themselves is assumed to approach infinity. This assumption has been shown by actual measurement to be erroneous; the lowest resistance to earth of a skid alone was measured by the author at 130 ohms on soil of about 1200 ohm metres resistivity, while the highest was measured at 375 ohms on soil of about 5800 ohm metres resistivity.

Figure 5.1

Typical present earthing arrangement



5.2 ALTERNATIVE METHODS OF REDUCING EARTH RESISTANCE AND SURGE IMPEDANCE OF AN EARTH ELECTRODE

5.2.1 *Introduction*

The resistance to earth of an earth electrode is a function of:

a) The surface area of the electrode in contact with the surrounding soil and,

b) The resistivity of the soil in the vicinity of the electrode. Of particular relevance is the resistivity of that volume of soil over which most of the resistance is dropped, this being in the immediate vicinity of the electrode.

5.2.2 Discussion

The earthing system presently employed endeavours to reduce earth resistance by increasing the surface area of the electrodes through the use of longer electrodes, and by using longer electrodes in order to take advantage of lower soil resistivities which typically occur at greater depths below the surface. However, as the resistivity decreases with depth, so too does the length of the electrode in contact with the lower resistivity soil. In addition, the practical aspects of having deep holes drilled in the field remain problematical.

It was therefore decided to investigate the feasibility of reducing electrode earth resistance by using a larger diameter electrode (increasing electrode surface area), and by wetting the soil in the immediate vicinity of the electrode (lowering soil resistivity).

5.2.3 An Experimental Wetted Electrode

An electrode was constructed in accordance with figure 5.2:

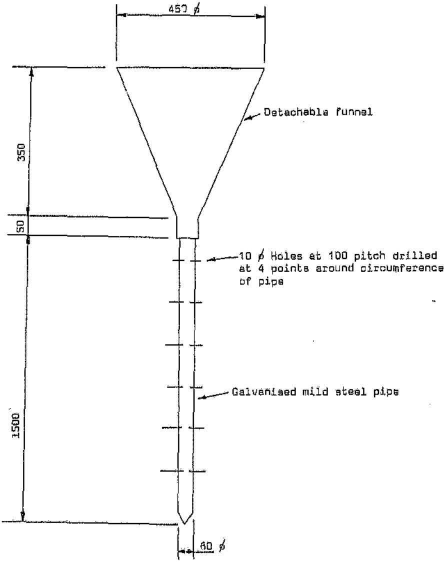


Figure 5.2

Experimental wetted electrode

A hole was made in the ground using a portable auger machine and the electrode then installed. The pipe was filled with coal dust and the resistance to earth was measured at 1,49 kilo ohms.

One kilogram of table salt was then poured into the funnel, which was then filled with potable water.

A drop in the measured value of resistance to 640 ohms was recorded within 10 minutes of adding water and table salt to the funnel. After 1 hour the resistance had dropped to 412 ohms. The resistance to earth was then measured at regular intervals over the ensuing weeks. The results of these measurements are plotted on graph 5.1.

The resistivity of the soil at the test site was then measured. The results of these measurements are shown in Table 5.1.

TABLE 5.1

SOIL RESISTIVITY AT EXPERIMENTAL ELECTRODE TEST SITE

Electrode separation(m)	Measured resistance (ohms)	Resistivity (ohm metres)
1	371,0	2321
2	304,0	3821
5	143,6	4510

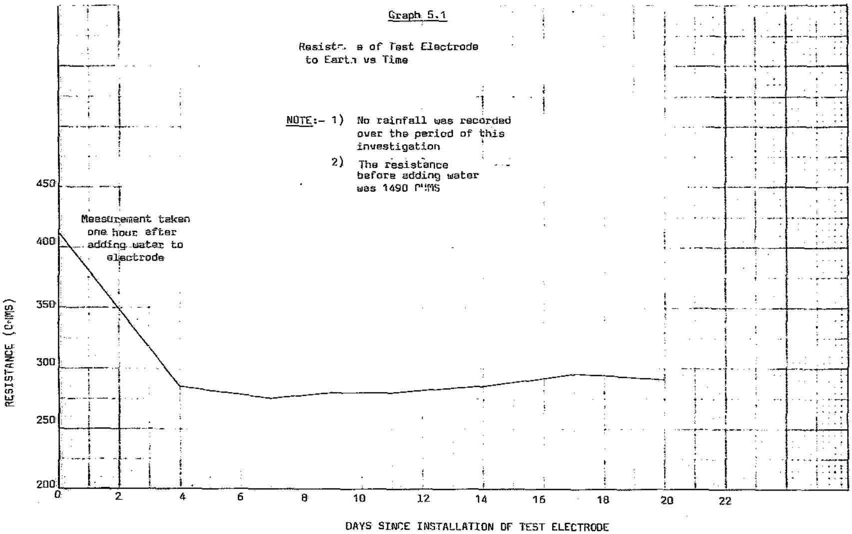
The results of this work indicate that a wetted electrode may prove to be a viable alternative to the installation of deep electrodes. The electrode resistance to earth when wetted was shown to be approximately one fifth of that when dry. In addition, although no further water was added to the electrode, either artificially or by natural precipitation, during the period of the test, the resistance did not increase significantly over the twenty days that the test was conducted.

It was concluded from this work that the observed reduction in the measured resistance to earth of the test electrode may be ascribed to any one or a combination of the following factors:

a) The reduction in soil resistivity *due to the soil being* wet.

b) The reduction in soil resisitivity due to table salt being *mixed with the water in the funnel.*

c) The enhanced electrode to soil contact which would occur when the electrode and surrounding soil was wetted.


Graph 5.1
Resist. e of Test Electrode to Earth vs Time
NOTE:- 1) No rainfall was recorded over the period of this investigation
2) The resistance before adding water was 1490 OHMS
Measurement taken one hour after adding water to electrode
450
400
350
300
250
200
RESISTANCE (OHMS)
0
2
4
6
8
10
12
14
16
18
20
22
DAYS SINCE INSTALLATION OF TEST ELECTRODE

5.3 TRIAL EARTHING SYSTEM EMPLOYING WETTED ELECTRODES

Four electrodes were installed around a mobile skid in a layout as shown diagrammatically in figures 5.3.

Initial resistance measurements were made as detailed in Appendix 4 for the skid alone, for the skid connected to the buried conductors, for the skid, buried conductors and electrodes interconnected, and finally with the electrodes filled with water. These measurements are summarised on graph 5.2.

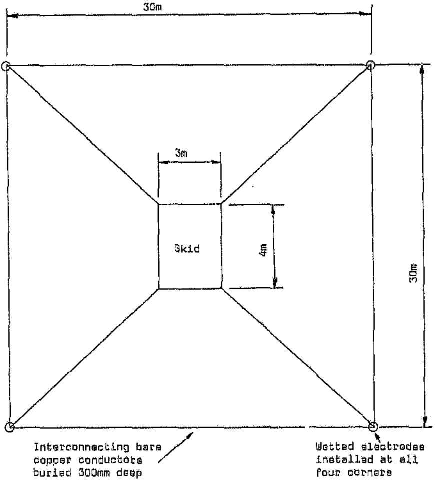
Soil resistivity was measured at the test site. The results of these measurements are given in table 5.2

TABLE 5.2

Electrode Spacing (m)	Measured Resistance (ohms)	Resistivity (ohm metres)
1	530	3 330
2	230	2 890
5	63	1 979
10	22	1 382

Figure 5.3

Layout of trial earthing system employing wetted electrodes



The soil, at the time that the resistivity measurements were made, was dry, no rain having fallen since the previous rainfall season.

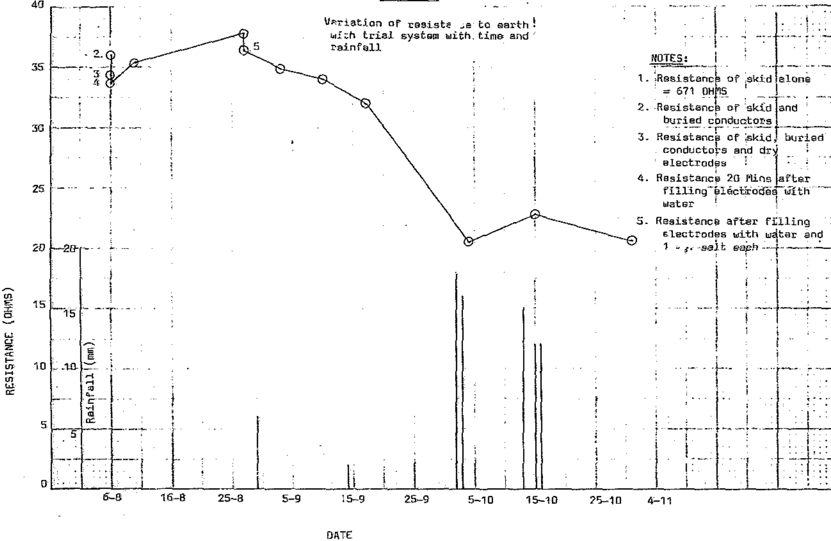
Further measurements of resistance were made over the ensuing weeks. These are detailed in Appendix 4 and are summarised on Graph 5.2

The following conclusions can be drawn from a perusal of the results obtained from the trial system and the experimental wetted electrode.

(a) It is essential that all conductive components of the earthing system be buried, in order to maximise the conductor area in contact with the surrounding soil. This is borne out by the drop in resistance of 635 ohms when connecting the buried conductors to the skid, as compared to the further drop in resistance of only 2,3 ohms when connecting the four vertical electrodes to the buried conductors, before adding water to the electrodes.

(b) It appears to be advantageous to add table salt to the wetted electrodes. On 6th August the trial system electrodes were wetted without adding salt, and the resistance had increased by 1,9 ohms by 10th August, (when water was still visible in one electrode), and by a further 2,20 ohm by 28th August (when all the electrodes were dry). On the 28th August water was again added to the electrodes together with 1kg of table salt per electrode. The resistance was then at all times lower than it was on 28th August. Although it is noted that rain was recorded after 28th August (see graph 5.2), and that this may be responsible for the resistance drops encountered, it is postulated that some advantage was gained by adding salt to the electrodes. Between 28th August and 17th September, a drop in resistance of 4,4 ohms (12%) was noted, although only 8 mm of rain was recorded over this period.

Graph 5.2


Variation of resiste _e to earth with trial system with time and rainfall
NOTES:
1. Resistance of skid alone = 671 OHMS
2. Resistance of skid and buried conductors
3. Resistance of skid, buried conductors and dry electrodes
4. Resistance 20 Mins after filling electrodes with water
5. Resistance after filling electrodes with water and 1 salt each
RESISTANCE (OHMS)
Rainfall (mm)
DATE
6-8
16-8
25-8
5-9
15-9
25-9
5-10
15-10
25-10
4-11
0
5
10
15
20
25
30
35
40

(c) With most of the earthing system consisting of conductors buried at about 300mm below the surface, rainfall obviously has a significant effect in reducing the resistance to earth of the earthing system. This can be readily seen from readings taken after 17th September. The efficiency of the inclusion of wetted electrodes cannot therefore be readily evaluated on the basis of the readings taken to date, as the trial system was established shortly before the onset of the rainfall season. However, on the strength of the significant reduction in electrode resistance noted during work with the experimental wetted electrode, it is postulated that during the dry season, the wetted electrodes will make an important contribution to keeping the earthing system resistance lower than would be the case with dry electrodes. Obviously this postulation will have to be thoroughly tested by continuing to monitor the resistance of the trial system throughout the forthcoming dry season and into the next wet season.

5.4 PROPOSED EARTHING SYSTEM

An earthing system employing short wetted electrodes will be easier to install and control than one employing long electrodes for which deep holes must be drilled. In addition, the author is of the opinion that testing of the trial system during the dry winter months will show the resistance to earth of the trial system to be significantly lower and more consistent than that of the present earthing system.

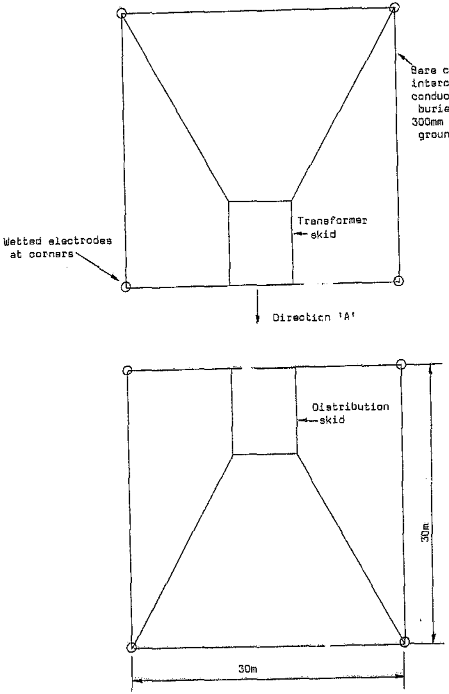
An earthing system based on the trial system is therefore proposed.

As it is desirable, as far as possible, to electrically separate the transformer skid and distribution skid earthing systems, (see Chapter 3) an earthing system layout as shown in figure 5.4 is proposed. While it is recognised that this system differs from the trial system, the differences are not significant.

Corrosion of the wetted electrodes is not expected to present any problems, as the skids are moved at intervals not normally exceeding six months.

Figure 5.4

Proposed earthing system



Ideally, when current flows through the transformer skid to earth, the distribution skid should not rise to a potential in excess of the maximum permitted touch potential, as any rise in potential of the distribution skid would also be experienced by the dragline due to the solid earth connection between them. The maximum permitted touch potential has been shown to be 80 volts for power frequency currents, and 900 volts for lightning discharge currents (Chapter 2).

If the potential of the dragline is elevated above that of true earth, this potential will be dropped between the dragline and true earth. A person standing next to the dragline and touching it will therefore not experience the full potential across his body, as shown in figure 5.5. If it is assumed that the maximum distance that a person will be standing away from a dragline while touching it is 1 metre, then the potential of the dragline can rise to 170 volts for power frequency current and 1915 volts for lightning discharge current, as it has been shown by measurement (Appendix 3, A3.5, page 59) that 47% of the resistance, and therefore the potential of a dragline to earth is dropped over the first metre away from the machine.

It can be assumed that the shape of the resistance versus distance curve away from the transformer skid will be the same for the proposed system as for the trial system, as any differences which may be present will not materially effect conclusions which can be drawn from the discussion which follows:

From a perusal of resistance measurements taken on the trial system, a typical value of resistance to earth of 35 ohms was chosen. This value is only applicable when power frequency and low magnitude currents are being considered. When the earthing system discharges a high magnitude and frequency current such as lightning stroke current, the impedance will be modified by travelling wave and soil ionisation effects.

Soil ionisation will occur in the vicinity of an electrode carrying a high current resulting in an increase in conductor effective radius and consequent decrease in impedance. The surge impedance can vary from 20% to 80% of the power frequency impedance, the former limit applying in the case of a single discrete electrode, where the current densities in the surrounding soil medium are high (5). However, when the earthing system is more distributed, as in the case in the proposed system, the current densities are lower

Figure 5.5

Curve of potential vs distance away from a dragline showing touch potential in relation to the maximum potential to which the dragline is raised

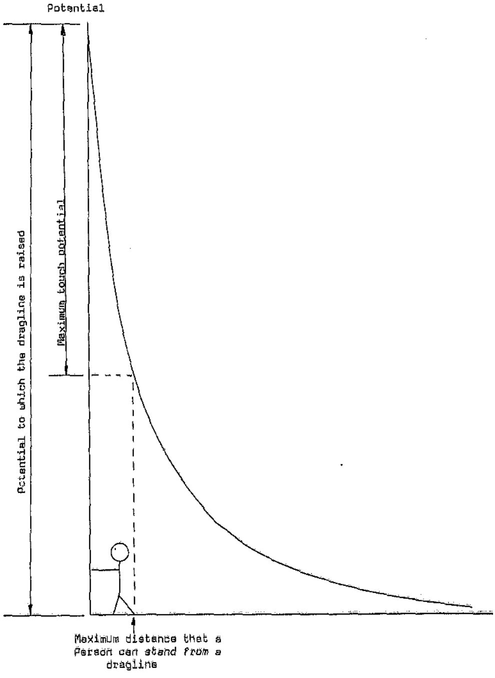
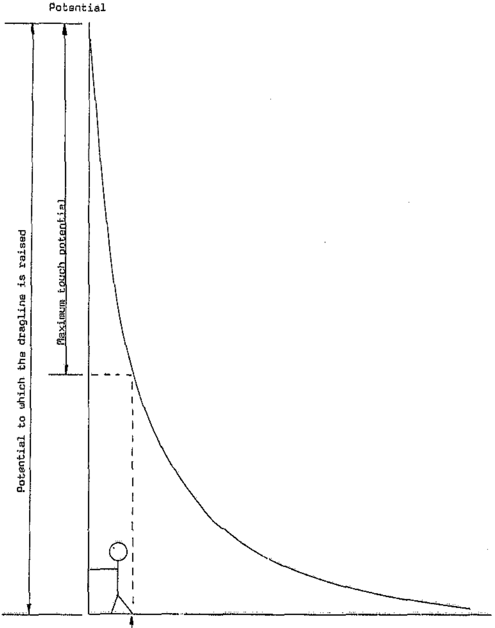


Figure 5.5

Curve of potential vs distance away from a dragline showing touch potential in relation to the maximum potential to which the dragline is raised



in the surrounding soil medium, and the effect of soil ionisation is not as marked. It is therefore proposed that in the case of the system proposed soil ionisation be conservatively estimated to decrease the impedance when discharging lightning stroke current to 80% of the power frequency impedance value, i.e. to 28 ohms from 35 ohms.

When a buried element of an earthing system is subjected to a high frequency current impulse the buried element acts as a transmission line and various reflections take place before the steady state condition is reached. The effect of this behaviour can be to either markedly increase or decrease the initial impedance of the earthing system (5). It has been shown that the most favourable effect can be attained by employing a combination of a high capacitance system of buried radial conductors in combination with a high conductance system of distributed driven rods. The earthing system proposed approximates to such a system. It is therefore assumed that travelling wave effects will cause a further reduction of 20% in the initial value of impedance when discharging lightning stroke current compared to the power frequency value. The initial impedance of the proposed system under lightning impulse conditions was therefore taken as 0,8 X 0,8 X 35 = 22,4 ohms.

A typical resistance versus distance curve for a resistance to earth of 35 ohms was available from measurements made on the trial system. If the asymtotic value of resistance were decreased to 22,4 ohms, the shape of this curve would be the same as that for 35 ohms, i.e.the percentage of asymtotic resistance dropped between any two points along the abcissas of both curves would be the same. A curve of impedance versus distance away from the transformer skid, as shown on graph 5.3 was thereby derived. A value of lightning stroke current of 34kA (see Chapter 3) was then assumed in order to derive a curve of the fall in potential versus distance away from the transformer skid. This curve is shown on graph 5.4. The maximum potential to which the transformer skid will rise is 34kA X 22,4 ohms = 761,6kV.

On the ordinate of graph 5.4 a potential of 1915 volts is equivalent to 0,06 divisions. The exact distance away from the transformer skid at which the equipotential line of 1915 volts occurs is difficult to predict with any degree of confidence as, although graph 5.4 depicts true zero potential as occuring at 35 metres away from the transformer skid, the curve only becomes asymtotic to true zero potential at this point. Theoretically, true zero potential occurs an infinite distance away from the transformer skid. The actual curve of potential versus distance may therefore lie 0,06 divisions on the ordinate (corresponding to 1915 volts) above true zero potential at a distance greatly in excess of 35 metres from the transformer skid.

It is therefore concluded that no practical separation of the transformer and distribution skid earthing systems can ensure that no dangerous rise in potential of the distribution skid will occur when lightning stroke current is discharged through the transformer skid earthing system. It is however recognised that the probability of a lightning discharge through the transformer skid earthing system causing a dangerous rise in the potential of the distribution skid decreases with increasing physical separation of the two skids.

When a power frequency fault to earth occurs on the transformer skid, the maximum potential to which the skid can rise is the transformer supply potential of 19 kV (phase). The value of resistance to earth of 35 ohms previously assumed will not be modified in any way by travelling wave effects. Soil ionisation can however occur, although it is felt that the effects of this will be insignificant. Persuing a similar argument to that put forward for the case of a lightning discharge, it can be shown that a potential of 170 volts will correspond to 0,31 divisions on the ordinate of the potential versus distance graph. Again the distance from the transformer skid to the 170 volt equipotential line cannot be confidently predicted.

It is therefore concluded that no practical separation of the transformer and distribution skid earthing systems will protect persons in the vicinity of 6,6 kV equipment from experiencing dangerous overvoltages should either power frequency or lightning stroke current be discharged through the transformer skid earthing system. The skids should therefore be located as far apart as practically possible.

Figure 5.4

Impedance to earth of the transformer skid versus distance away from the skid

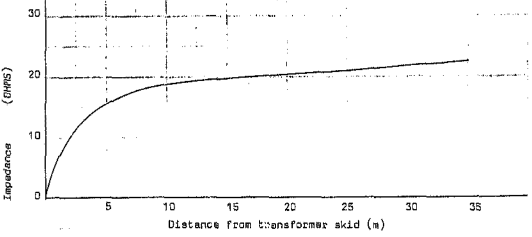
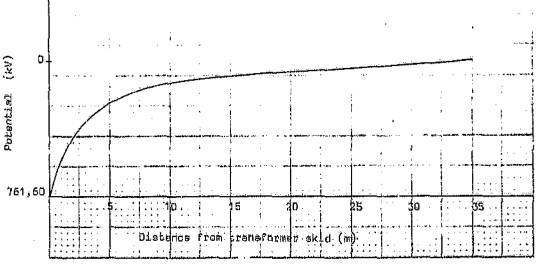


Figure 5.5

Potential with respect to true earth versus distance away from the transformer skid when a 34 kA lightning stroke is discharged through the skid



CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 *THE EARTH ELECTRODE SYSTEM*

It is recommended that the transformer and distribution skids be earthed by means of an earthing system employing wetted electrodes. Such a system is more fully described in Chapter 5. This system has the following more important advantages over the system presently used:

a) The recommended system is easier to install than the present system, with one functional department of the mine being responsible for all aspects of the installation. Management control over the correct earthing system installation will therefore be improved.

b) It is expected that the proposed earthing system will exhibit a lower and more consistent value of impedance to earth, both for power frequency and lightning stroke current discharges than the present system.

6.2 PROTECTION OF PEOPLE FROM OVERVOLTAGES DUE TO LIGHTNING

Nothing can be done to ensure that dangerous step or touch potentials will not occur due to the flow of lightning current through either the transformer or distribution skid earthing systems. It is therefore necessary to ensure as far as possible that people in the vicinity of equipment do not come into contact with these potentials. In order to achieve this the following list of recommendations is proposed.

a) The transformer and distribution skids should be installed as far apart as practically possible, as the severity of overvoltages occuring on the distribution skid due to lightning stroke current discharges through the transfromer skid earthing system decreases as the distance between the two skids increases.

b) A blanket prohibition should be established on people touching mobile equipment from the ground when lightning activity is present.

c) Gates on all transformer and distribution skids should be inset by about 1 metre from the edge of the skid, as is current practice on some mines. This measure ensures that one must be standing with both feet on the skid before the relatively time consuming task of unlocking the gate can be undertaken.

d) Handrails of all stairways leading onto mobile equipment should be insulated, or manufactured from insulating material. This will ensure that should the equipment be at a dangerous potential the path of current flow will be from foot to foot, and not hand to foot. The insulation used should be substantial, preferably exhibiting an impulse flashover value of not less than 200kV.

e) All workers should wear thick soled rubber boots, which should be kept in a good condition.

f) Although human fatalities are rare due to step potentials in the ground, the current flow always being from foot to foot (10), it is recommended that people be prohibited from approaching mobile equipment and skids on foot when lightning activity is present.

g) People should not stand closer than 2 metres away from mobile equipment or skids when lightning activity is present, in order to protect themselves against side flashes from the equipment.

6.3 PROTECTION OF PEOPLE FROM POWER FREQUENCY OVERVOLTAGES

The limitation of earth fault current on the 6,6kV reticulation system to 25 Amps is sufficient to ensure that dangerous step and touch potentials will not occur due to faults on this system. (Chapter 3).

Earth fault current on the 33 kV system is not limited. Therefore, in addition to taking those steps suggested for avoiding dangerous lightning overvoltages, it is suggested that consideration be given to increasing the zero sequence impedance of the 33 kV system in order to limit t current. A limiting value of 200 Amps to 300 Amps would be appropriate (9). In addition, the 33kV protection scheme could be checked to ensure that earth faults are cleared in the shortest possible time.

6.4 PROTECTION OF EQUIPMENT DUE TO LIGHTNING OVERVOLTAGES

Although a rigorous insulation co-ordination study should be carried out, it is suggested that the following steps could contribute to reducing the rate of equipment failure presently being experienced.

a) Surge diverters are presently installed at the overhead line termination to the transformer skid. While these arrestors provide adequate protection of the skid mounted voltage transformer and circuit breaker, similar protection is not afforded to the transformer, as the distance between the surge diverters and the transformer 33kV terminals is too great (8). Additional diverters should therefore be mounted on the terminals of the transformer. The connection between these surge diverters and the grounding point common to the transformer should be so arranged so as to be as short as possible and to have as low a reactance as possible.

b) The 6,6kV overhead line connection between the transformer and distribution skids should be protected against lightning strikes. This can most easily be achieved by erecting a finial on the transformer skid, of sufficient height to provide an acceptable level of protection to the 6,6kV lines.

ACKNOWLEDGEMENTS

The author wishes to thank the *Directors of Rand Mines (Mining and Services) Ltd.* for the opportunity to carry out this work. Further thanks are also due to all those who were of assistance in the preparation of this report, especially to the project co-supervisers for their support and edification during the course of this work, and to the personnel of the various mines visited by the author, particularly Messrs. J Rodgers and J Bezuidenhout of Middelburg Mine for their assistance in the field work undertaken. Sincere thanks are due to *Mesdames L. van Heerden and T. Bryan* who typed and retyped the manuscript. Finally, the author acknowledges with thanks the contribution made to this work by his wife, for her support and *ability to spell correctly.*

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APPENDIX 1

RESISTIVITY MEASUREMENTS MADE ON DUVHA MINE

	1	2	3	4	5	6	7
POSITION (metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)
2	3029	3633	3331	2112	6008	260	4173
4	2134	3292	2389	1003	5378	359	3568
6	1252	2131	2040	577	3808	369	2243
8	799	1403	1066	588	3237	366	1503
10	-	-	-	-	-	362	898
12	777	1154	1071	434	1320	-	589
14	-	-	-	-	-	245	-
16	444	618	987	543	873	-	383
18	-	-	-	-	-	210	-
20	328	516	772	430	760	-	324
22	-	-	-	-	-	210	-
24	383	590	569	312	661	-	281
26	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-
30	426	675	243	158	405	211	241

POSITION	8	9	10	11	12	13	14
INTERVAL (metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)
2	1664	1395	527	341	152	1433	1647
4	1010	877	485	156	247	1302	1606
6	777	592	319	134	273	792	1885
8	558	500	235	136	335	414	1886
10	426	-	-	-	-	-	-
12	-	458	155	148	327	212	1610
14	563	428	-	-	-	-	-
16	-	436	166	150	279	124	1900
18	610	-	-	-	-	-	-
20	-	-	127	-	-	-	1507
22	-	-	-	-	250	106	-
24	-	-	133	-	-	-	1519
26	-	-	-	-	-	-	-
28	-	-	-	-	-	-	-
30	992	584	100	211	296	98	1599

POSITION	15	16	17	18	19	20	21
INTERVAL (metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)
2	5531	1003	3155	3821	5606	2439	3608
4	2990	1365	2714	4900	3996	3192	4825
6	2255	1357	1625	4222	2993	2654	4222
8	925	1362	1091	3931	1971	2227	3534
10	564	1232	710	2978	-	-	-
12	-	-	-	-	935	1500	2270
14	198	161	731	2261	-	-	-
16	-	-	-	-	599	961	1930
18	108	959	706	1222	-	-	-
20	-	-	-	-	647	799	1872
22	115	1035	654	934	-	-	-
24	-	-	-	-	706	908	2141
26	-	-	588	879			-
28	-	1049	-	-			2270
30	130	782	609	846			1952

APPENDIX 2

RESISTIVITY MEASUREMENTS MADE ON RIETSPRUIT MINE

POSITION	1	2	3	4	5	6	7
INTERVAL (metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)
2	501,54	255,17	657,41	906,30	142,04	1382,70	605,87
4	439,77	364,38	291,51	1045,41	177,42	796,62	482,50
6	294,77	392,08	193,78	987,74	196,42	343,45	298,58
8	205,60	373,00	177,45	744,00	196,56	212,64	182,48
10	153,31	322,95	176,55	595,63	202,94	133,20	103,67
12	116,12	303,86	165,13	321,20	227,71	101,04	85,96
14	103,79	276,19	144,25	368,55	263,00	67,73	76,53
16	98,52	262,38	147,78	292,54	287,51	56,30	76,40
18	98,40	234,12	144,77	262,39		55,42	68,99
20		202,31	128,17	243,78			
22		197,67					

POSITION	8	9	10	11	12	13	14
INTERVAL (metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)	RESISTIVITY (ohm metres)
2	256,43	9,18	467,60	199,86	476,40	751,69	1696,95
4	195,01	14,83	193,00	227,43	500,09	851,91	976,50
6	163,24	19,23	93,87	324,22	433,55	912,34	686,14
8	157,85	22,62	63,34	363,45	395,62	643,46	532,86
10	147,02	24,50	53,41	368,18	346,19	529,03	400,23
12	142,51		51,02	391,33	306,88	479,51	341,56
14	146,01		42,22	437,16	280,59	421,33	326,33
16	148,78			370,96	259,37	363,92	298,57
18	139,11				210,37	324,60	242,03
20					184,72		217,39

POSITION	15	16	17	18
INTERVAL (metres)	RESISTIVITY (Ohm metres)	RESISTIVITY (Ohm metres)	RESISTIVITY (Ohm metres)	RESISTIVITY (Ohm metres)
2	61,47	1319,85	321,79	155,87
4	60,06	1723,92	369,41	138,97
6	62,58	1534,39	317,43	130,44
8	74,90	1060,70	321,23	125,17
10	77,91	747,68	362,53	130,69
12	81,43	581,33	324,97	134,97
14	88,84	467,95	318,42	147,77
16		443,34	292,54	133,70
18		444,48	252,21	
20		436,04	228,70	

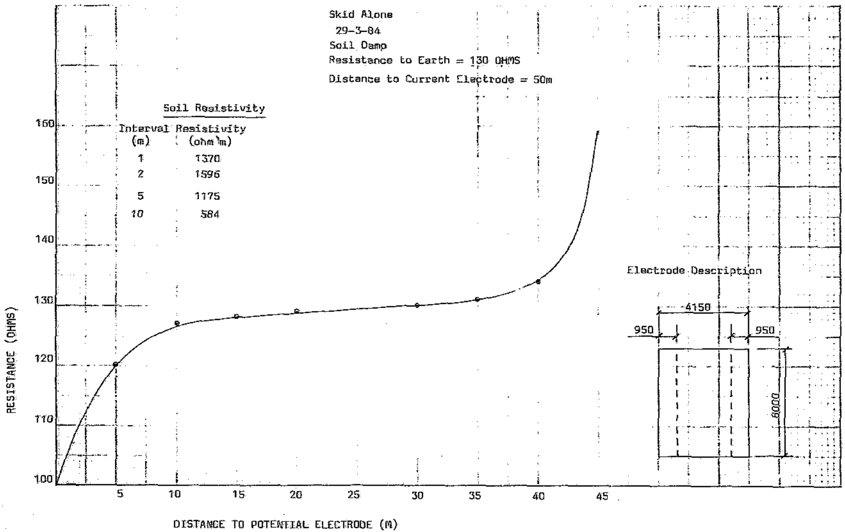
POSITION	15	16	17	18
INTERVAL (metres)	RESISTIVITY (Ohm metres)	RESISTIVITY (Ohm metres)	RESISTIVITY (Ohm metres)	RESISTIVITY (Ohm metres)
2	61,47	1319,85	321,79	155,87
4	60,06	1723,92	369,41	138,97
6	62,58	1534,39	317,43	130,44
8	74,90	1060,70	321,23	125,17
10	77,91	747,68	362,53	130,69
12	81,43	581,33	324,97	134,97
14	88,84	467,95	318,42	147,77
16		443,34	292,54	133,70
18		444,48	252,21	
20		436,04	228,70	

APPENDIX 3

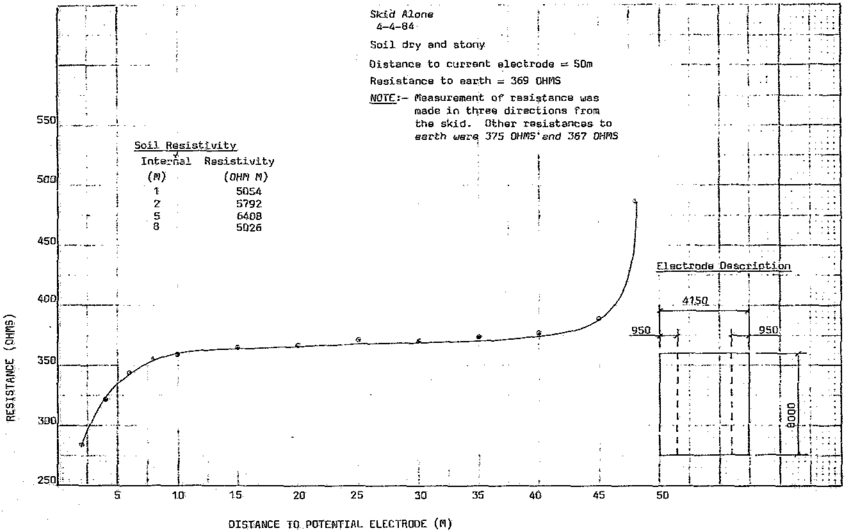
RESISTANCE AND RESISITVITY MEASUREMENTS MADE BY THE AUTHOR - A REPRESENTATIVE SELECTION OF MEASUREMENTS TAKEN

<u>NOTE</u>: A total of 20 measurements of resistance to earth of various items of mobile machines and electrode configurations were made by the author. Resistivity measurements were made at 6 sites. Five such measurements are included in this Appendix, these being representative of all the measurements made.

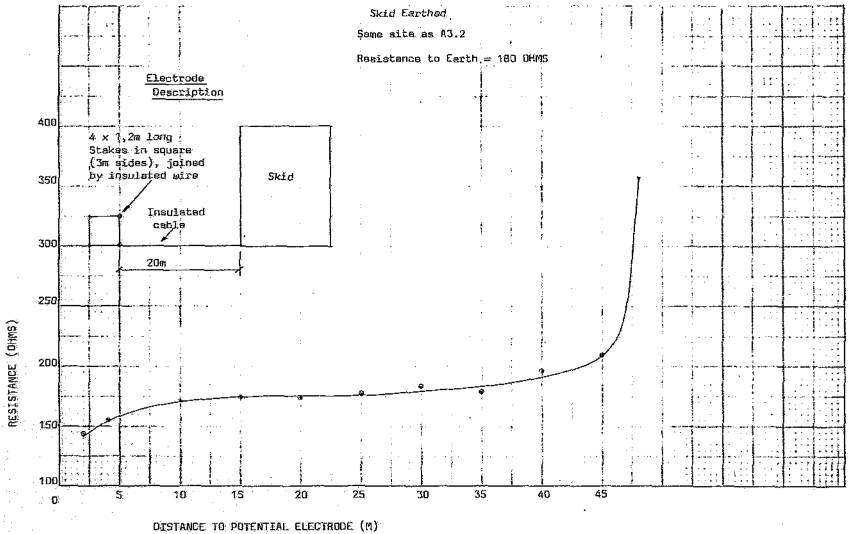
A3.1


Skid Alone
29-3-84
Soil Damp
Resistance to Earth = 130 OHMS
Distance to Current Electrode = 50m
Soil Resistivity
Interval (m)
Resistivity (ohm m)
1
1370
2
1596
5
1175
10
584
Electrode Description
4150
950
950
6000
RESISTANCE (OHMS)
100
110
120
130
140
150
160
5
10
15
20
25
30
35
40
45
DISTANCE TO POTENTIAL ELECTRODE (M)

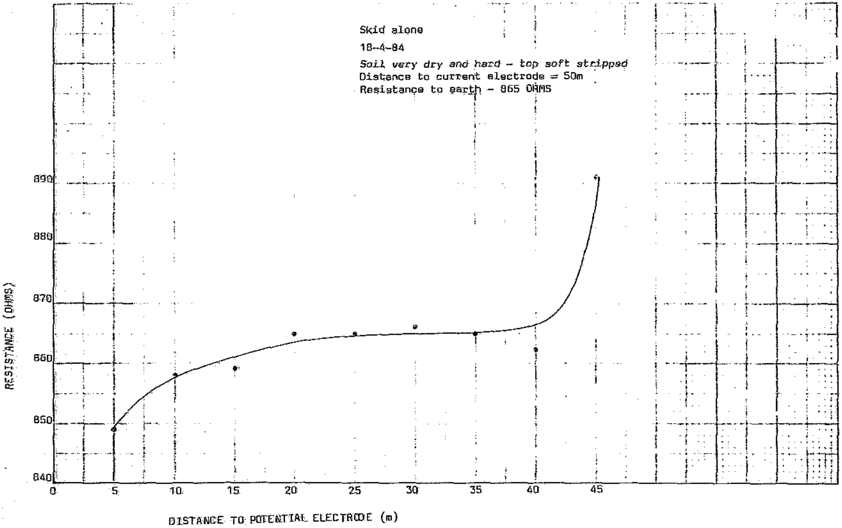
A3.2


Skid Alone
4-4-84
Soil dry and stony
Distance to current electrode = 50m
Resistance to earth = 369 OHMS
NOTE:- Measurement of resistance was made in three directions from the skid. Other resistances to earth were 375 OHMS and 367 OHMS
Soil Resistivity
Internal Resistivity
(M) (OHM M)
1 5054
2 5792
5 6408
8 5026
Electrode Description
4150
950
950
8000
550
500
450
400
350
300
250
RESISTANCE (OHMS)
5
10
15
20
25
30
35
40
45
50
DISTANCE TO POTENTIAL ELECTRODE (M)

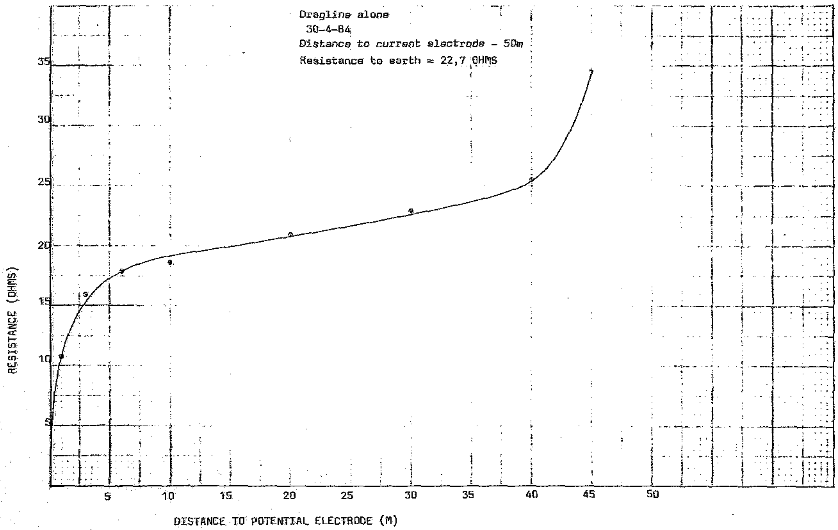
A3.3


Skid Earthed
Same site as A3.2
Resistance to Earth = 180 OHMS
Electrode Description
4 x 1,2m long Stakes in square (3m sides), joined by insulated wire
Insulated cable
Skid
20m
RESISTANCE (OHMS)
100
150
200
250
300
350
400
0
5
10
15
20
25
30
35
40
45
DISTANCE TO POTENTIAL ELECTRODE (M)

A3.4


Skid alone
18-4-84
Soil very dry and hard - top soft stripped
Distance to current electrode = 50m
Resistance to earth - 865 OHMS
RESISTANCE (OHMS)
890
880
870
860
850
840
0
5
10
15
20
25
30
35
40
45
DISTANCE TO POTENTIAL ELECTRODE (m)

A3.5



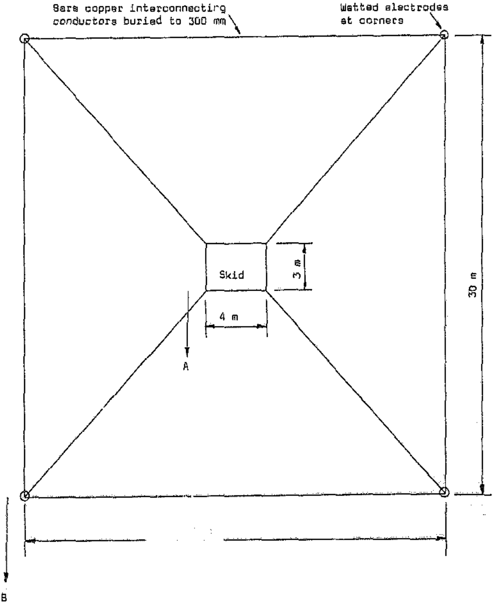
Dragline alone
30-4-84
Distance to current electrode - 50m
Resistance to earth = 22,7 OHMS
RESISTANCE (OHMS)
5
10
15
20
25
30
35
DISTANCE TO POTENTIAL ELECTRODE (M)
5
10
15
20
25
30
35
40
45
50

APPENDIX 4

RESISTANCE MEASUREMENTS MADE ON THE TRIAL SYSTEM

1. EARTHING SYSTEM DESCRIPTION

The earthing system consisted of a skid, buried interconnecting conductors, and four wetted electrodes as shown diagrammatically below.



2. INITIAL MEASUREMENTS

Date 6 August 1984

Soil conditions: Dry

Direction of measurement: A

Distance to current electrode: 55m

Distance to potential Electrode (m)	Case 1 (Ohms)	Case 2 (Ohms)	Case 3 (Ohms)	Case 4 (Ohms)
5	645	22,1	21,2	20,0
10	657	24,5	23,8	22,4
20	665	31,1	28,7	27,5
30	671	36,0	34,3	33,7
40	675	39,4	38,4	36,9
50	701	68,0	66,5	66,1

Case 1: Resistance of skid alone

Case 2: Resistance of skid connected to buried conductors.

Case 3: Resistance of skid, buried conductors and electrode interconnected.

Case 4 As for [illegible] but 20 minutes after the electrodes were filled with wa[illegible] (no salt added).

3. SUBSEQUENT MEASUREMENTS

3.1 Date: 10 August 1984

Soil Conditions: Dry

Direction of measurement: A

Distance to current electrode: 51m

Water visible in 1 electrode

Distance to Potential Electrode (m)	Measured Resistance (Ohms)
5	20,0
10	22,2
20	27,3
30	3[illegible]
40	39,[illegible]
48	181,0

3.2 Date: 10 August 1984

Soil conditions: Dry

Direction of measurement: B

Distance to current electrodes: 55m.

Water visible in 1 electrode

Distance t[illegible] Potentia[illegible] Electrod[illegible] [illegible]m)	Measured Resistance (Ohms)
5	26,7
10	28,0
20	30,3
30	33,2
40	35,0
50	60,4

3.3 Date: 28 August 1984

Soil conditions: *Dry*

Direction of measurement: B

Distance to current electrode:50m

All electrodes dried out

Distance to Potential Electrode (m)	Measured Resistance (Ohms)
10	31,2
20	33,4
30	37,8
40	42,1
46	62,2

3.4 Date: 28 August 1984

Soil Conditions: Dry

Direction of measurement: B

Distance to current electrode: 50m

All electrodes filled with water and one kilogram of table salt each.

Resistance measured at 61,8% of distance to current electrode measured immediately after filling electrodes with water and salt: 36,4 ohms

Date	Measured Resistance to earth (Ohms) (Note 1)	Rainfall (Note 2)
30/08/84	-	6mm
3/09/84	34,9	-
10/09/84	34,0	-
14/09/84	-	2mm
17/09/84	32,0	-
2/10/84	-	18mm
3/10/84	-	16mm
4/10/84	20,5	-
12/10/84	-	-
13/10/84	-	15mm
15/10/84	22,8	12mm
16/10/84	-	12mm
31/10/84	20,6	-

NOTE: 1 Resistance measurement taken with potential electrode at 61,8% of distance from earthing system to current electrode (50m)

NOTE: 2 No further water was added to the electrode, other than that added by natural precipitation.

APPENDIX 5

INSTRUMENT USED FOR RESISTANCE AND RESISTIVITY MEASUREMENTS

A Metraterr 2 earth resistance meter was used to measure resistance and resistivity. Salient specifications of this instrument are as follows:

a) Frequency of measuring voltage: 108 $\pm$ 3 Hz.

b) Measuring range: 0,1 ohms to 9,99 kilo ohms.

c) Rated operating conditions : To VDE 0413 Part 5.

d) Operation temperature range: 10°^{C} to + 55°^{C}.

e)

Measuring range	*Open circuit* voltage	Short circuit current
0 - 9,99 ohms	40V A.C.	40 mA A.C.
0 - 99,9 ohms	40V A.C	40 mA A.C.
0 - 999 ohms	250V A.C.	3 mA A.C.
0 - 9,99 K ohms	250V A.C.	3 mA A.C.