系統識別號：C09006343

行政院所屬各機關因公出國人員出國報告書
（出國類別：會議及研習）

「地下管線腐蝕防制及洩漏偵測研討」

服務機關：中國石油煉製研究所
出國人職稱：技術服務組工程師
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出國地點：美國
出國日期：90/10/14－90/10/27
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公務出國報告提要

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報告名稱：

地下管線腐蝕防制及洩漏偵測研討

主辦機關：

中國石油股份有限公司

聯絡人/電話

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出國類別：研究
出國地區：美國
出國期間：民國 90 年 10 月 14 日 －民國 90 年 10 月 27 日
報告日期：民國 91 年 01 月 22 日
分類號/目：I0/綜合（科學類）I0/綜合（科學類）
關鍵詞：陰極防蝕，地下管線、雜散電流
內容摘要：

地下管線埋設於地下，受到土壤水份、硫酸根離子、氯離子的影響，會造成管線鋼鐵材料的腐蝕，本公司之地下管線皆採用包覆，以避免材料直接暴露在腐蝕性的土壤中，此為基本的防蝕，此外更應用了陰極防蝕系統，來加強管線的抗蝕，使地下管線能避免包覆破裂的腐蝕，並且可以持續延長管線的防蝕壽命。但是外界環境的變化，使得管線所處的情況更為惡劣。「外界干擾」所引發的腐蝕更為嚴重，由於外界干擾的產生源、發生時間、強度、頻率等無法用一般的檢測方式來察覺，因此防制的方法更為困難。「外界干擾」最明顯的來源是雜散電流；例如捷運系統或其他直流電源，這種雜散電流產生的腐蝕是局部的，因此會造成管線產生孔蝕，這種攻擊可以讓輸油管線於極短的時間穿孔，使油品外洩，污染環境，由於此種問題在台灣仍屬新遭遇的現象，因此本次奉派出國主要的任務便是參加美國 Cathodic Protection Management 公司所舉辦的 Stray Current Class（雜散電流課程），主要目的為了瞭解雜散電流干擾的發生機制，檢測的方法及獲得防制的方法，於課程中瞭解到雜散電流的危害性，而也獲得檢測的方法，可以對本公司在地下管線腐蝕及洩漏湞測提供相當大幫助。課程結束後，前往洛杉磯 Borin 公司參觀遠端監控在地下管線防蝕上的應用，希望能將此類技術引進國外，提供防蝕監測的建立，使本公司的輸油管線能即時獲得良好的防蝕電流，最終目的為提高操作安全，增長使用壽命，進而提高競爭力。

本文電子檔已上傳至出國報告資訊網

摘要

地下管線埋設於地下，受到土壤水份、硫酸根離子、氯離子的影響，會造成管線鋼鐵材料的腐蝕，本公司之地下管線皆採用包覆，以避免材料直接暴露在腐蝕性的土壤中，此為基本的防蝕，此外更應用了陰極防蝕系統，來加強管線的抗蝕，使地下管線能避免包覆破裂的腐蝕，並且可以持續延長管線的防蝕壽命。但是外界環境的變化，使得管線所處的情況更為惡劣。「外界干擾」所引發的腐蝕更為嚴重，由於外界干擾的產生源、發生時間、強度、頻率等無法用一般的檢測方式來察覺，因此防制的方法更為困難。「外界干擾」最明顯的來源是雜散電流；例如捷運系統或其他直流電源，這種雜散電流產生的腐蝕是局部的，因此會造成管線產生孔蝕，這種攻擊可以讓輸油管線於極短的時間穿孔，使油品外洩，污染環境，由於此種問題在台灣仍屬新遭遇的現象，因此本次奉派出國主要的任務便是參加美國 Cathodic Protection Management 公司所舉辦的 Stray Current Class（雜散電流課程），主要目的為了瞭解雜散電流干擾的發生機制，檢測的方法及獲得防制的方法，於課程中瞭解到雜散電流的危害性，而也獲得檢測的方法，可以對本公司在地下管線腐蝕及洩漏滇測提供相當大幫助。課程結束後，前往洛杉磯 Borin 公司參觀遠端監控在地下管線防蝕上的應用，希望能將此類技術引進國外，提供防蝕監測的建立，使本公司的輸油管線能即時獲得良好的防蝕電流，最終目的為提高操作安全，增長使用壽命，進而提高競爭力。

關鍵詞：陰極防蝕，地下管線、雜散電流

地下管線腐蝕防制及洩漏偵測研討出國報告

目　次

一、前言

雜散電流是一種在土壤環境中流竄且不可控制的電流，可能為直流型式亦可能為交流型式，發生的時間可能是突發性的或持續性的，它是地下鋼鐵材料加速腐蝕極為嚴重的腐蝕因子。因為當雜散電流的傳遞經過地下管線或儲油槽時它所引起的是電化學防蝕的逆向反應，它的攻擊力（腐蝕）集中而強烈，亦即產生的雜散電流集中攻擊儲送管線或油槽的局部，因此管線及油槽在短短的數年之間即可造成穿孔而導致油品外漏，根據文獻記載當雜散電流大小在 1mA/cm^2，每年將減薄 1.2mm。

直流及交流型式的雜散電流中直流雜散電流的腐蝕強度十倍於交流雜散電流。而依發生源而言誘發雜散電流的有大眾捷運系統、接地系統及大地電流，其中最令人關注的是大眾捷運系統所產生的雜散電流。

大眾捷運系統將台電供應的 161KV 交流電降壓整流轉換成 750V 直流電經由第三軌供給電聯車組使用，第三軌為傳送電流之主要路徑為正極，它通常鋪設於地面或列車行車面架設，驅動聯車之電流流經接地電刷後流至行車軌回流之變電站，行車軌為電聯車回流電流之路徑，為防止電流經行車軌洩漏之週圍環境，因此行車軌下方均襯有絕緣墊，甚至裝有雜散電流集電設備以做為二級防護。但是裸露鋪設在地面的行車軌所輸送的電流非常容易透過軌道和地面的接觸流入土壤，加上台灣高溫潮濕、鹽份、塵土的附著，都會增加電流散失量，因此可斷言未來散電流的腐蝕問題將愈來愈明顯。

大眾捷運系統的建立代表我國社會經濟的進步與繁榮，大台北地區的雙十路網捷運系統已正式通車，而台中及高雄都會捷運系統亦在規劃中。防止都會區大眾捷運系統雜散電流所引起的地下儲運設備腐蝕便顯得刻不容緩，因此為希望能及早瞭解台北地區大眾捷運系統對本公司加油站及儲運設備雜散電流影響的範圍、影響的程度及消除方法。

二、行程及工作摘要

時　　間	行　　　　程	地　　點
90.10.14	啟程飛往美國芝加哥	芝加哥/依利諾州
90.10.15 | 90.10.22	參加 CPM 公司 Stray Current Training 課程	芝加哥
90.10.23 | 90.10.24	參加 Borin 公司提線陰極防蝕監控方案與最新發展現況研究會	舊金山
90.10.25	參觀 Borin 公司陰極防蝕監控現場觀摩	洛杉磯
90.10.26 | 90.10.27	由洛彬機搭機返台	台北

三、訓練課程內容說明

本次參加CPM公司雜散電流課程，主要目的為瞭解直流雜散電流的機制及檢測方法，課程主要內容如下：

1. 直流雜散電流之成因
    - (1)不同運量捷運雜散電流之種類。
    - (2)產生雜散電流之捷運軌道因子。
    - (3)直流動力回路。
    - (4)軌道對地電位。
    - (5)捷運位置對雜散電流大小的影響。
    - (6)軌道電阻對雜散電流之影響。
    - (7)軌道構造對雜散電流之影響。
    - (8)軌道連續性對直流雜散電流之影響。
    - (9)直流雜散電流的模式。
    - (10)雜散電流影響接地電位差。
2. 直流雜散電流的偵測
    - (1)管對地電位變動
    - (2)雜散電流傳送方式
        - a. 電位基本準位
        - b. 陰極區
        - c. 陽極區
    - (3)雜散電流流動方向
    - (4)土壤之電位梯度
3. 直流雜散電流的測試程序
    - (1)管對地電位的時間關係
    - (2)管對地電位與相對位值的關係
    - (3)Beta Plot 的原理
4. 檢測儀器介紹
5. 雜散電流的確認
    - (1)腐蝕位置
    - (2)雜散電流的大小評估
6. 消除直流雜散電流之方法
    - (1)捷運系統業者的改善
        - a. 軌道的絕緣加強
        - b. 加強軌道的連續性
        - c. 降低軌道的接地性
    - (2)以外加電流系統改善雜電流
        - a. 外加電流陽極的位置
        - b. 外加電流需求量
    - (3)犧牲陽極改善雜散電流

(4)以金屬連結改善軌道連續性

7. 監控及檢測程序
   (1)測試導線的連結
   (2)永久參考電極
   (3)試片
   (4)校正
   (5)使用資料記錄器
   (6)遠程監控

8. 問題的解析
   (1)管線電位的時間變化
   (2)雜散電流的大小
   (3)Beta slope 圖

9. 現場課程

至美國 Lakehead Pipe Line 公司位於 Griffith 地區之油庫進行實習課程。

二、參加美國 Borin 公司所舉辦之陰極防蝕監控方案與最新發展現況研討會

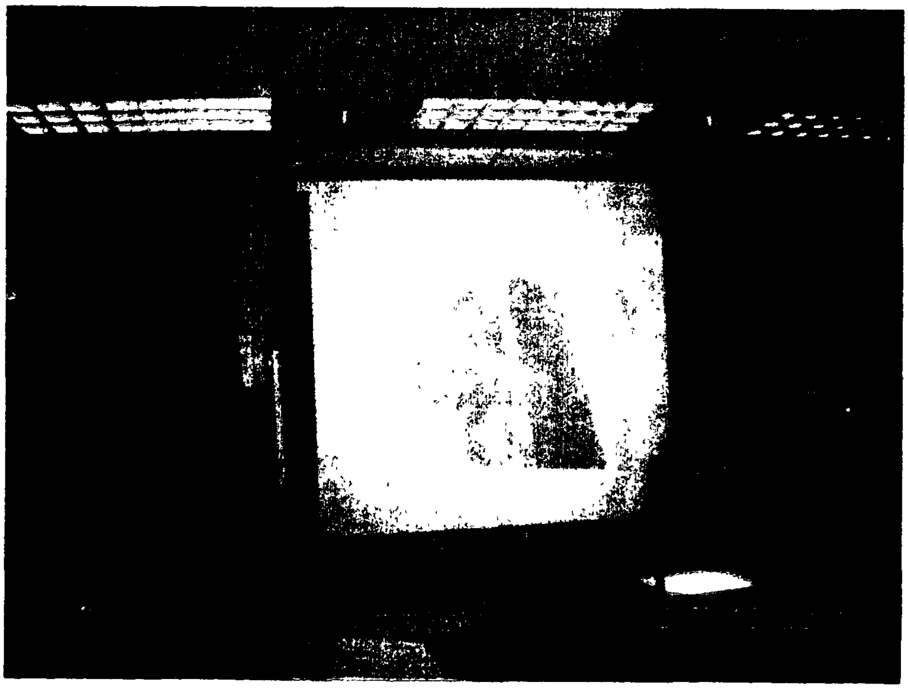
美國 Borin 公司為陰極防蝕檢測設備之製造公司，其總公司位於加洲洛杉磯，主要產品為監測用之參考電極及遠端監控設備，本次該公司假舊金山 Handry 飯店舉辦研討會，介紹該公司產品及監測技術的研討，參加者除有管線儲槽擁有公司如 ENBRIDGE、LARKHEAD、陰極防蝕公司，如 MCM、T&R、CORRPRO、其他還有非防蝕界，但可能用到監控設備者如電廠及石化廠，會中提出四篇報告，討論遠端監控的發展，應用外也討論了實際的作法，其中以透過直升機飛越管線上空，以讀取管線電位及利用無線技術遙讀資訊，令人印象深刻。利用直升讀取管線電位資訊，是先在管線的監測點架設該線發射器，這時及定頻發射無線電波由空中接收，其最大的好處是可以取得長途管線每一監測點的電位，對於管線的防蝕狀態，可全般瞭解，但安裝的成本太高，且每次的執行成本也不小，但的確適用石管線長度較長的地區。而利用無線遙讀，則是利用使用極為普遍的行動電話來讀取陰極防蝕地區的資料，它同時也可以有線之方式來進行資料的取得，但無法獲得每一監測點的電位，但由於成本低，但又可獲得部份重要的資料，相當值得引進。

會後部份參予人員又飛往洛杉磯的 Marina Del Ray 地區參觀該公司，將此設備應用在監控 Marina Del Ray 港口的防蝕。該港口之碼頭基礎是利用外加電流系統，提供鋼管樁的防蝕，其監控的主要點為提供陰極防蝕的整流站，利用遠端監控介面來讀取現有資料，並據以更新電流輸出。

三、心得與建議

本次出國參加雜散電流訓練課，可以配合目前本公司所遭遇到的管線雜散電流府蝕。瞭解其發生或因發生的機制，及頻率也獲得監測的方法，及消除的方式，使職對於未來的工作助益良多，而遠端監測建立則走可以提高研究層次，及幫助本公司降低成本即時提供正確數據，以增加管線操作安裝最佳方法，此一技術將在本年落實，使遠端監控能實際應用化。

參加訓練課程之 ENBRIDGE 公司油槽區



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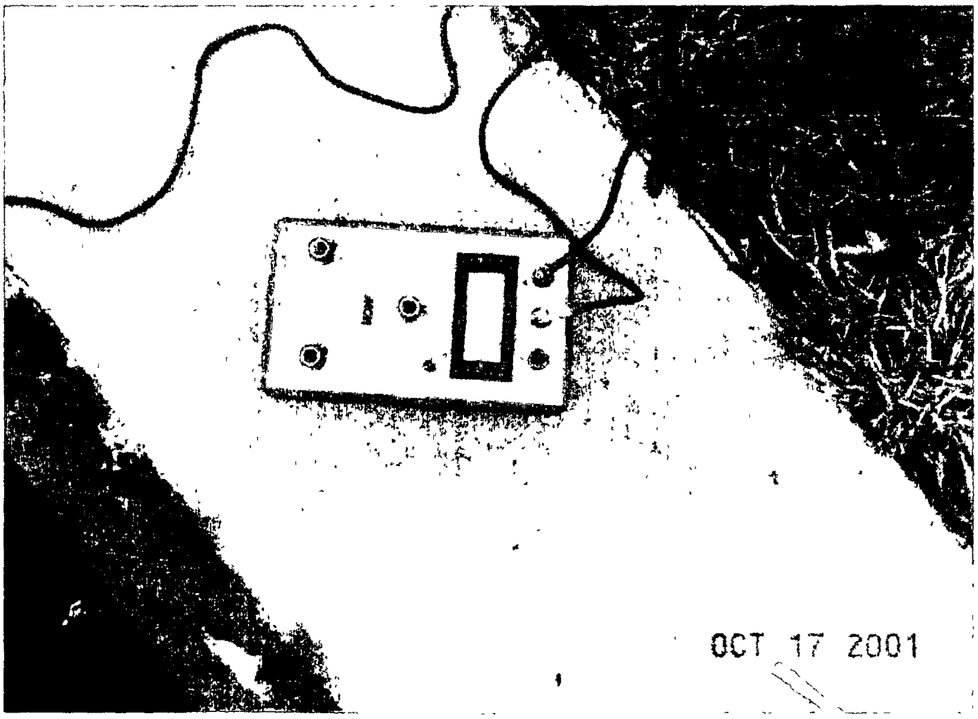
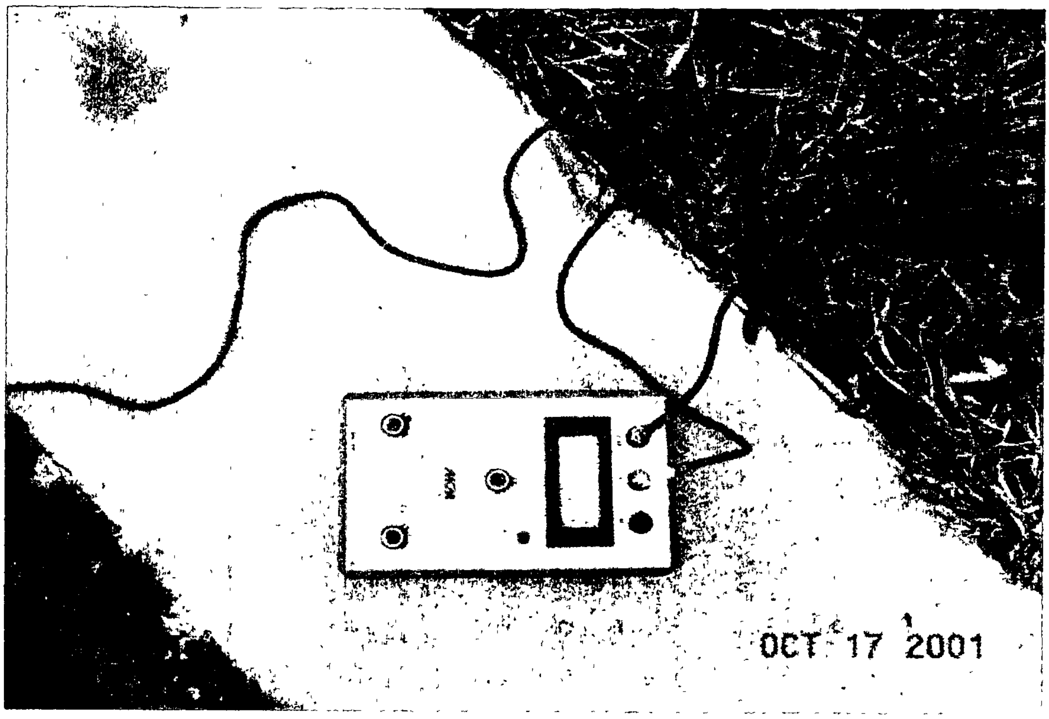
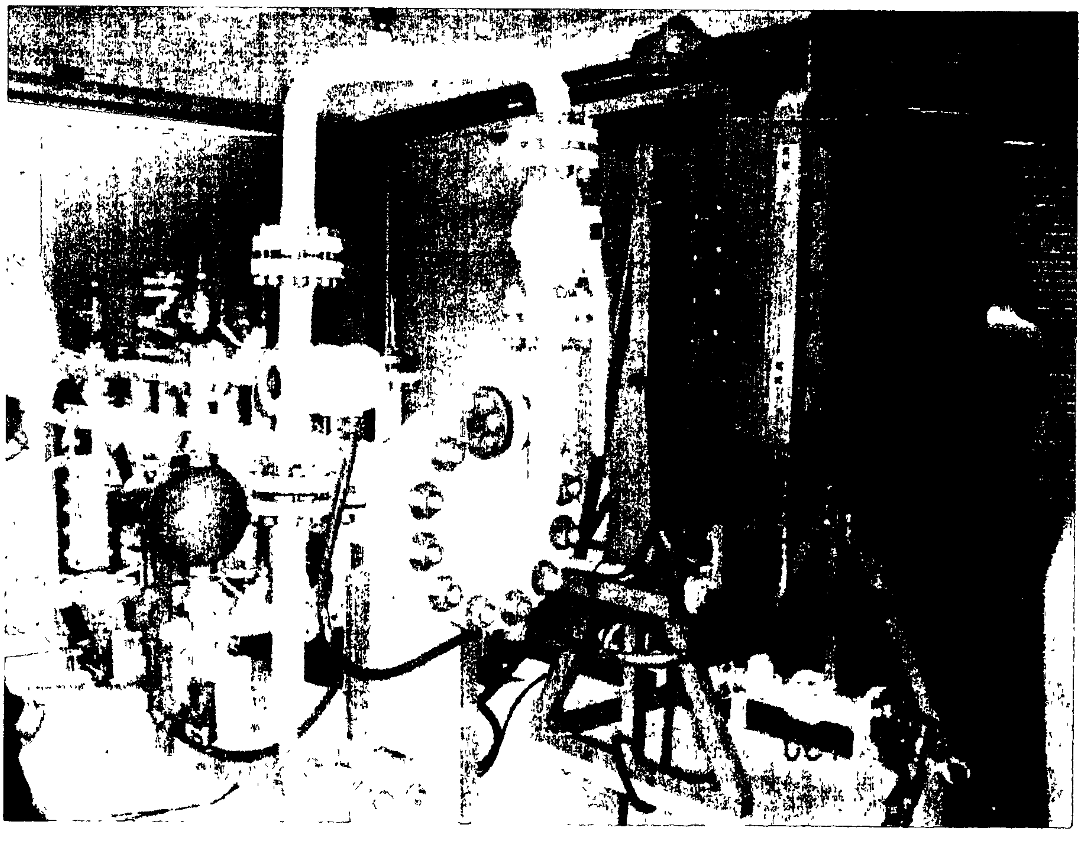
講師 DENNIS 上課情況



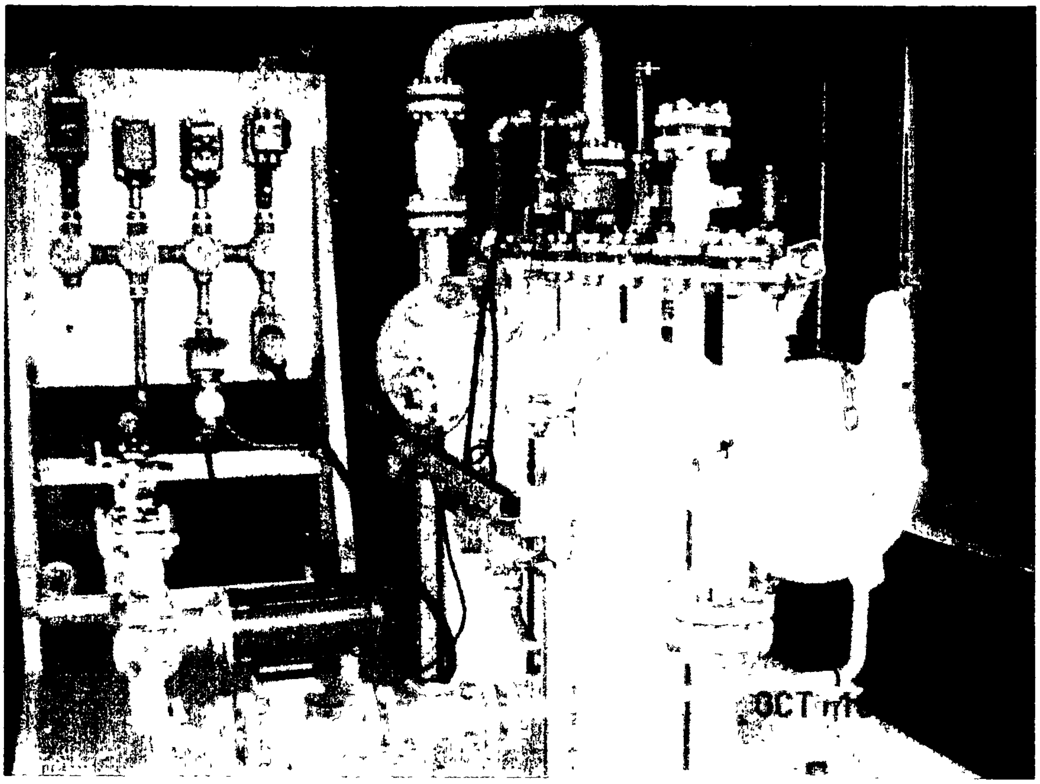
現場檢測



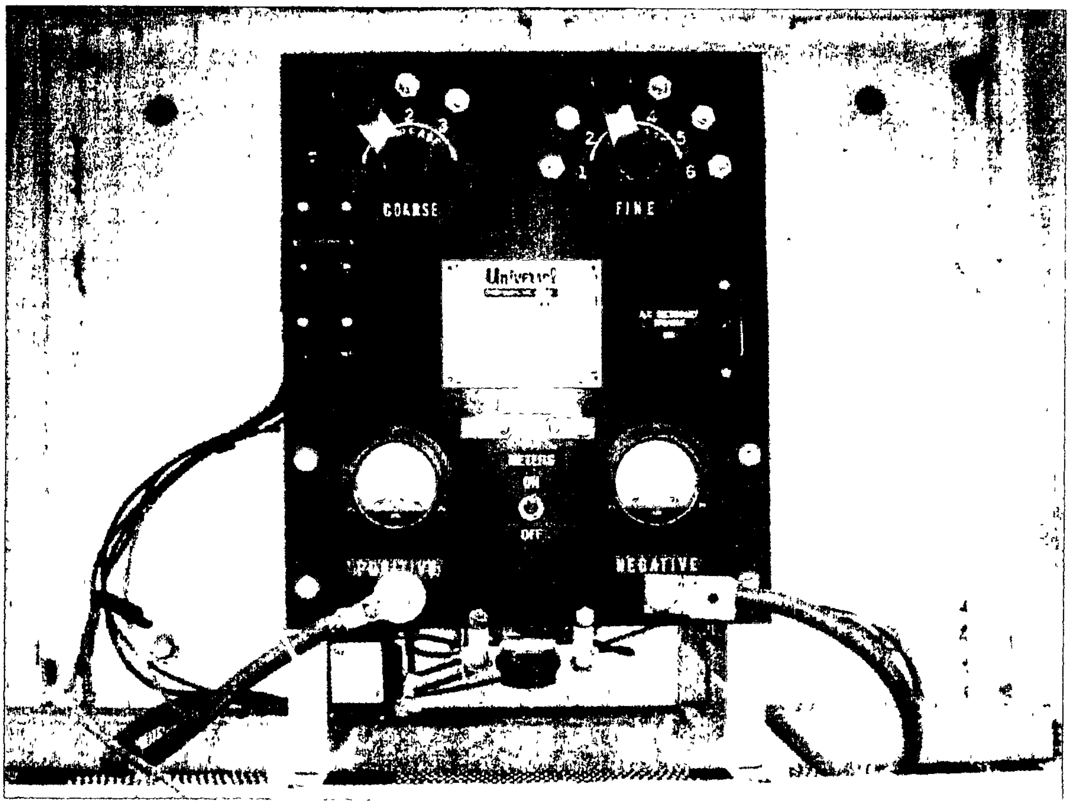
現場檢測



管內腐蝕監控

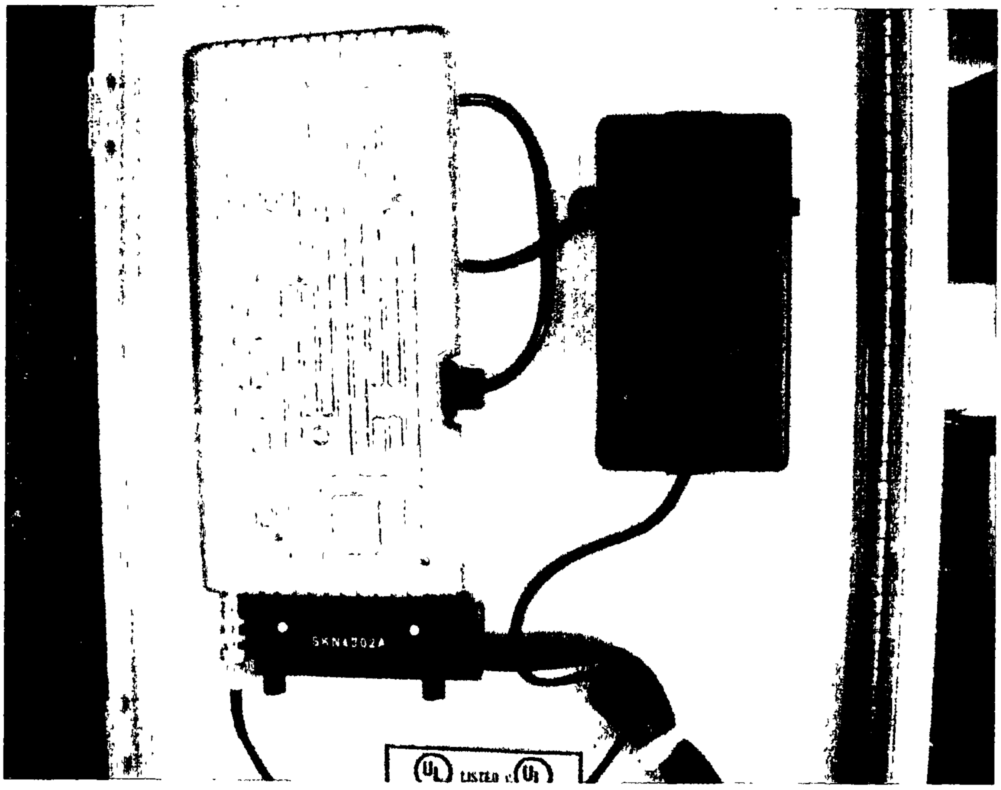


現場檢測



現場整流器操作及檢測

BORIN 公司遠端監控在碼頭陰極防蝕之應用



BORIN 公司遠端監控設備

附件

2001 IEEE/ASME JOINT RAIL CONFERENCE
TORONTO, ONTARIO, CANADA
April 17-19, 2001

ANALYSIS OF STRAY CURRENT, TRACK-TO-EARTH POTENTIALS &SUBSTATION NEGATIVE GROUNDING IN DC TRACTION ELECTRIFICATION SYSTEM

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Abstract:

In the first part of the paper, we will look at a stray current model under the ideal conditions with uniformly distributed track-to-earth resistances and develop the track-to-earth potentials and stray current relationships within a segment of track. We then will expand the model to include buried metallic structures in the vicinity of the track using field theory to calculate the potential gradients generated due to flow of rail current and show that a potential difference experienced by a crossing or paralleling underground structure that traverses these gradients could cause stray current corrosion. We will discuss the limitations of these models with the actual conditions such as non-uniform track-to-earth resistances, non-uniform soil resistivities.

In the second part, we will look at the stray current model when there are inadvertent breakdowns in the track insulation. The points of rail insulation breakdown may be approximated using the spherical ground electrode model and equipotential lines to illustrate the flow of stray current. Common grounding of the substation negative bus, substation ac ground mat and electric utility neutral will be examined and discussed.

PART 1: STRAY CURRENT MODEL WITH UNIFORMLY DISTRIBUTED TRACK-TO-EARTH RESISTANCES

Introduction:

Historically, rails have been considered as the least expensive negative return conductor for dc traction electrification systems. Designers of modern dc rail transit system must address the following issues about rails:

- Traction power engineers want to use the rails as a continuous negative return conductor for traction current and possibly to ground the rails temporarily when the high rail potential rise could pose a danger to personnel and passengers.

- Signal engineers may want to isolate the rails by section, and thus use them as power frequency train control circuits for track occupancy indication.

- Corrosion engineers want to insulate rails from ties and ballast to minimize stray traction power currents as a cause of corrosion.

These different and conflicting demands must be dealt with and satisfied. To maintain continuity for dc traction current and allow rail isolation for track circuits, impedance bonds will be used. Stray currents can be mitigated effectively by increasing the track-to-earth resistances. However, this could elevate the track-to-earth voltages under certain operating conditions.

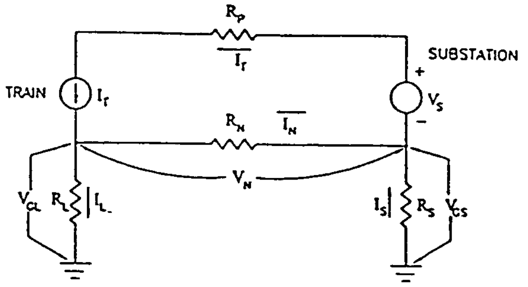
This paper will mainly focus on stray current control, track-to-earth potentials and grounding of the traction power substation negative. Various circuit models are developed to analyze stray current and track-to-earth potentials under various conditions.

Basic Stray Current Model

To illustrate the basic components affecting the levels of stray currents generated by a dc traction power system, a simple radial feed circuit model is shown in Figure 1. This model assumes that the resistance of the overhead contact system to ground is very high and there is no coupling between the positive circuit and earth.

From this model, the three basic components which control the level of leakage stray currents to ground are:

I_T *: The train current.*
V_N *: The voltage developed across the negative circuit resistance(*R_N*).*
R_L & R_S *:The effective resistance between the negative circuit and earth.*



R_N : RESISTANCE OF NEGATIVE RETURN CIRCUIT
R_P : RESISTANCE OF POSITIVE CIRCUIT
R_L : TRACK-TO-EARTH RESISTANCE AT THE LOAD END
R_S : TRACK-TO-EARTH RESISTANCE AT THE SOURCE END
I_T : TRAIN OPERATING CURRENT
I_N : CURRENT RETURN THROUGH THE RAILS
I_L : LEAKAGE CURRENT TO EARTH AT THE LOAD END
I_S : CURRENT RETURNING TO THE SUBSTATION THROUGH EARTH
V_S : SUBSTATION VOLTAGE
V_{CL} : TRACK-TO-EARTH VOLTAGE AT THE LOAD END
V_{CS} : TRACK-TO-EARTH VOLTAGE AT THE SUBSTATION LOCATION
V_N : VOLTAGE DEVELOPED ACROSS R_N BY I_N

Figure 1- Basic Stray Current Model

Although these three items are interrelated as described later in subsequent parts of this paper, each item must be considered separately.

The magnitude of the train current(I_T) required to operate a light rail vehicle is power dependent, i.e., for a stated power requirement to provide for a certain acceleration under a given set of conditions, the current required will vary depending on the voltage. Hence, an increase in operating voltage would allow a proportional decrease in the current, and would be a benefit to stray current limitation. Most modern dc transit systems are designed for the 600 to 800Vdc range. Seattle Sound Transit Link light rail will be the first modern light rail system that utilizes 1500Vdc in North America.

One consideration in maintaining train operating voltage within acceptable limits and minimizing the generation of stray currents as the vehicle moves away from the power source is to keep the substation as close to the point of maximum load as possible. This may require the use of more substations than otherwise would be necessary.

The second factor requiring consideration is the resistance of the negative return circuit, referred to as R_N in Figure 1. Stray current is a function of the track circuit potential or negative rail potential. This potential, V_N, is the voltage developed across the negative return rail from the substation to the train and it depends on the train current(I_T) and R_N. There are two basic approaches to maintain the voltage developed across the negative return system within the desired limits, assuming a given propulsion power requirement: a) Increase the conductance of the negative return circuit; b) Reduce the maximum distance between the load and power source as also noted above, which means spacing between traction power substations would need to be reduced, which may result in an increase of the number of substations.

The third factor affecting the stray current magnitudes in the model of Figure 1 is the negative circuit to earth resistance, referred to as R_L &R_S. Theoretically, we could reduce the stray current by increasing R_L &R_S to very high values.

Stray Current Model Used For Computer Simulation

The actual model generally used for computer stray current studies is shown in Figure 2. The actual dc powered transit system utilizes a number of traction power substations that are interconnected, and finite negative circuit to earth resistance. The characteristics of the negative return circuit or running rails are those of a distributed network with a unit length of track(s) composed of longitudinal resistance of the rail conductors and the track-to-earth resistances.

Train movement and current draw is a continuously changing situation in a transit system. The model shown in Figure 2 is a dynamic circuit model and one approach that we have found very useful in analyzing stray currents is to take snapshots of the dynamic system with various train operating conditions, different traction power substation locations, varying the resistances within the negative and positive circuits, changing the effective negative circuit to earth resistances, etc.

This type of computer study provides the information that can be used as the basis for decisions regarding what level of stray currents could occur under various loading and operating conditions. This information provides a basis for evaluating the stray current effects on underground utility or other underground metallic structures and decisions on trade-offs between stray current control versus mitigation.

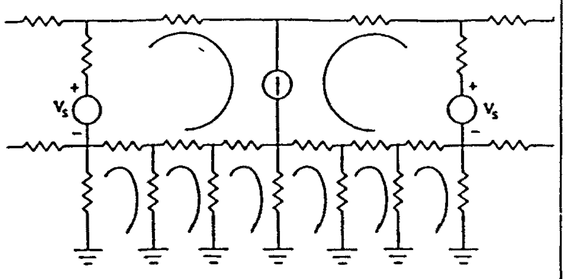


Figure 2-Computer Simulation Stray Current Model

Stray Current Control

The following accepted rail industry standards have been used in recent rail transit system designs to achieve an electrically isolated rail system to control stray currents:

- Insulating pads and clips on concrete ties.
- Insulating direct fixation fasteners on aerial structures.
- Coating the rails and encasing the track slab with an insulating membrane where the rails are embedded in the roadway areas.
- Minimizing the stray current leakage path through rail/ballast contact by maintaining the ballast at a minimum of 1-inch below the bottom of the rails.
- Bonding rail jumpers at mechanical rail connections for special trackwork.
- Cross-bonding between rails to maintain equal potentials of all rails.
- Insulating the impedance bond tap connections from the housing case.
- Insulating switch machines at the switch rods.
- Utilizing separate traction power substations for the main line, yard and shop. Shop tracks are solidly grounded for maintenance personnel safety.
- Installing rail insulators to electrically isolate the mainline from the yard and the yard from the shop.
- Maintaining as close substation spacing as practicable.
- Maintaining electrical continuity in tunnel liners and reinforcing steel.
- Maintaining an on-going maintenance program that monitors rail-to-earth resistance values, keeps trackbed areas clean and well-drained.

Track-to-Earth Voltages

As mentioned earlier, stray currents can be controlled effectively by increasing the track-to-earth resistance values. However, a well insulated negative return system will also cause the increased track-to-earth voltages.

The relationships between the voltages, V_N , V_{GL} and V_{GS} as shown in the basic circuit model of Figure 1 are summarized below:

$$V_{GL} \approx \frac{R_L}{R_L + R_S} x\ V_N$$

$$V_{GS} \approx \frac{R_S}{R_L + R_S} x\ V_N$$

Where: $V_N = I_N x\ R_N$

The profile of negative rail potential with respect to distant earth is shown in Figure 3, with an isolated substation negative bus.

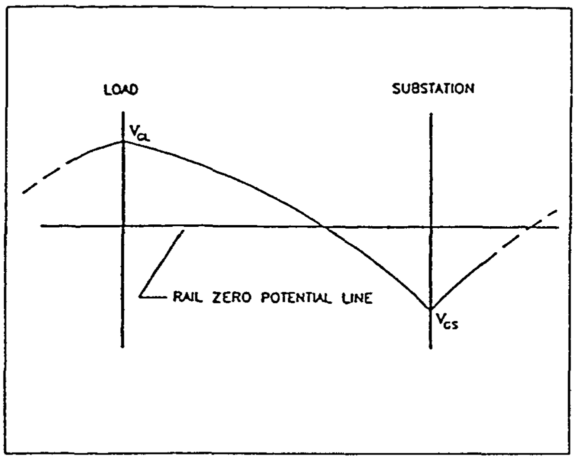


Figure 3- Negative -to-ground potential profile

The main concern which relates to this voltage is the human body's safety from touch potential. The rail transit industry has not standardized the acceptable limits of negative return rail potential with respect to ground. Each transit agency has set its own limits. Based on our past experiences, the maximum limit ranges from 60 volts to 90 volts dc.

Voltages alone are not harmful. It is the electric current passing through the human body that gives an electric shock and discomfort, not the voltage.

Human Body Curent - Electrical Circuit Model

The human body electrical circuit include the feet contact resistance, R_1, and the internal body resistance, R_2. A foot contact resistance is equal to $3\rho_S$ ohms, where ρ_S is the surface resistivity in ohm-meters underneath the foot. For two feet in parallel, the contact resistance R_1 is equal to $1.5\rho_S$.

Consider:

$R_1 = 1.5\rho_S = 1.5 \times 100\text{ohms} = 150$ ohms, based upon $\rho_S = 100$ ohm-meters for surface resistivity of wet concrete floor.

$R_2 = 1000$ ohms(internal body resistance for an average person)

The current passing through the body is:

$$I = \frac{E}{1150\ ohms}\ amperes$$

where E is the touch potential.

$I = 2.0ma(minimum\ perception),\ E = 2.3V$

$I = 60.0ma(maximum\ threshold),\ E = 69.0V$

$I = 80.0\ ma(maximum\ allowable),\ E = 92.0V$

Personnel safety can be enhanced by limiting the electric current passing through the human body. There are two ways to achieve this:

- Reduce the touch potential, E, to the lowest practical values such as *70V* or less.
- Increase contact resistance for foot and hand.

The following should be taken into considerations for personnel safety in designing dc traction power system:

- Substation ac switchgear and other ac equipment enclosures including the pre-fabricated substation building enclosure should be connected to a substation ac ground mat designed per IEEE std 80.

- Rectifier and dc switchgear equipment enclosures should be insulated from ground and connected to a dc ground mat through either a high-resistance or a low-resistance grounding system. Refer to reference [2] for additional discussions on high versus low resistance grounding.

- Adequate clearance and isolation should be provided between the grounded ac equipment and the insulated dc equipment.

- Use high resistivity materials such as granite edging, surface coatings, tile surfaces, etc. to increase passenger station platform surface resistance.

Earth Potential Gradient Model and Stray Current Effects on Buried Metallic Structures .

The earth potential gradient model measures the potential developed between two points in the earth and the magnitude of this potential will have direct stray current effects on buried utility structures. Refer to figure 4, the earth potential gradient is calculated from the following equation:

$$E = \frac{\rho . I}{\pi . l} . \ln \frac{d_1}{d_2}$$

Where:

ρ : *Soil resistivity, ohm-cm*
I : *Current from source, amperes*
d_1 : *distance from source to.structure*
d_2 : *distance from source to structure*
l : *length of current source(parallel rail), cm*

This equation can be used to calculate the potential difference between any two points in earth that will be traversed by the underground pipe or other buried structure. It should be noted that this equation has some limitations: a) soil resistivity, ρ, in the areas within the given length, l, of the pipe is assumed to be uniform; b) theoretically, the presented equation has no limit, however, the maximum calculated earth potential gradient produced by stray current cannot exceed the track-to-earth potential at a given location along the rails; c) assume that the earth potential gradients between at any two points are unchanged and will not get distorted due to the presence of pipes .

Figure 4 illustrates the potential difference between two points on an uncoated underground pipe. As shown in this figure, the pipeline is modeled as a distributed resistance network. Past experience has indicated that earth potential gradients at 50mv or below generally introduce acceptable stray current levels on most uncoated underground pipes or buried structures.

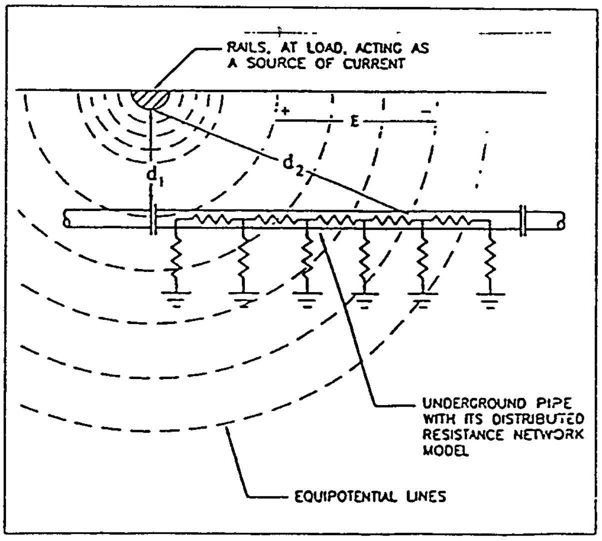


Figure 4 - Earth Potential Gradient Model

Substation Negative Return Grounding

Negative system grounding at the substation is employed by some modern rail transit authorities to limit the rail-to-earth potentials. This is accomplished by diode grounding, contactor/switch grounding, or thyristor grounding.

When there is a ground fault between the OCS and ground, the area in the vicinity of the fault could subject to a high voltage of 750 Vdc. Since the return circuit back to the traction power substation is closed via the earth to track because the substation negative bus is isolated, the ground fault current can be relatively low and the time it takes for the dc feeder breaker to clear the fault will be unduly long. A diode grounding device will provide a return path from the ground to the substation negative bus and thus enable faster fault clearing. However, the grounding diodes will also allow system leakage current to return to the substations thus creating a lower resistance path for stray current leaving the rails.

Contactors equipped with voltage sensing relays are also used for negative bus grounding. The voltage sensing relays will detect the high track-to-earth voltage situations and close the grounding contactor to connect the negative bus to ground temporarily for personnel safety.

The third negative grounding method is using the floating negative automatic grounding switch which consists of dc potential and current monitoring circuits and two thyristors connected to provide bi-directional control of current flow between the negative bus and ground. The circuitry monitors the potential between the negative system and ground. In the event the potential exceeds a predetermined voltage and time setting, the corresponding thyristor (depending upon the polarity) will activate thus clamping the negative bus to ground. Once activated, the thyristor will continue to conduct until the current reduces to zero or until the polarity reverses across the thyristor.

In an underground system, there is no direct metallic connections between earth and the rectifier negative bus. This system obviously has least stray leakage current but could have high negative potential to ground. More on substation negative return grounding is discussed in the second part of this paper.

PART 2: USING SPHERICAL ELECTRODE MODEL TO ANALYZE STRAY CURRENTS WHEN THERE ARE INADVERTENT BREAKDOWNS IN TRACK INSULATION

Introduction:

The Basic Stray Current Model and the Computer Model discussed in the first part of this paper have the limitation that they only apply when the track-to-earth resistance is relatively uniform, or put another way, the total resistance of the track is distributed evenly over its length. It cannot be used to predict the behavior of the traction electrification return system, rails and rail isolation if there is a ground on the return rails.

The traction electrification design engineer is interested in predicting the behavior of the traction electrification system under all conditions, including where grounds are present on the return rails when the rails are used as the negative return, as in modern light rail and trolley systems.

In this second part of the paper, we would like to present a method of calculating stray currents through earth, using grounding theory developed in IEEE Standard 80 - 1986[1].

Why use the spherical electrode model in analyzing stray currents? There are several reasons:

- When we discuss currents flowing through earth, a better understanding will be gained by using Ohms law quantified in terms of electric field potential strength, soil resistivity, and current density (*e*=*ir*).
- Resistance to earth is concentrated in shells closely surrounding a ground electrode, so a discussion of the electrode itself is important to understanding how currents flowing from it through earth behave.
- By varying the radius of electrodes, we can simulate varying resistances-to-earth and we can model and explore how the system behaves when the track is grounded, and explore many other topics related to design such as:
    1. Does grounding the substation negative bus through a diode, contactor, or thyristor increase stray currents?
    2. Does connecting the utility grounding system to the traction power substation ac ground system increase stray currents?
    3. If the substation negative return is grounded through a diode, contactor, or thyristor, should a separate dc grounding mat be used, and if so, what separation through ground will be sufficient to attenuate flow of stray current from the dc system to the utility grounding system?

Spherical electrode analysis with this type of approach requires track-to-earth resistances to be lumped and concentrated at an equivalent electrode. Secondly, it will be necessary to convert earth resistance to electrode radius in meters, as we shall see.

We have chosen the spherical ground electrode as a beginning point to represent a solid ground anywhere on the rails since it is the simplest to analyze. Another consideration is that even though the magnitude of the resistance to earth is determined by the type and size of electrode, once the distance from the electrode exceeds several times the radius of the electrode, the resistance of the earth to the flow of current becomes negligible. We could have as easily chosen a driven rod as an electrode, however we are not primarily interested in the characteristics of the electrode itself, rather how we may define a ground on the rail system that might represent conveniently as possible an actual physical rail to earth connection, and provide a mathematical basis for modeling the results of such a connection.

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[1] Portions of this discussion and accompanying figures are taken directly from IEEE Std 80 Appendix H, and reprinted here with permission. Copyright 1986 IEEE All rights reserved.

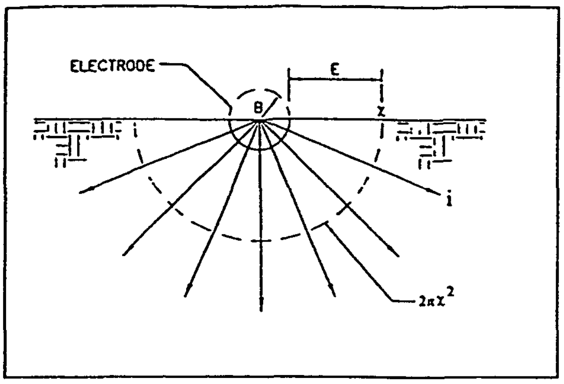

Fig 5 - Spherical Electrode

The surface area of a sphere is given as $4\pi r^2$. Consider a sphere with only the lower hemisphere buried in earth with uniform resistivity as shown in Figure 5, such that the area in contact with earth is given by $2\pi r^2$. If a current I flows through this electrode to ground, the current density i is evenly distributed over the surface of the sphere, and at a distance x from the center of the hemisphere is given by:

(1) $$i=\frac{I}{2\pi x^2}$$

Where *i=current density (amp/meter)*

According to Ohms law, an electric field of intensity e (see Figure 6) is generated when such a current flows through soil with a resistivity ρ.

(2) $$e=\rho\frac{I}{2\pi x^2}$$

The voltage E can then be computed as the line integral of the field strength from the surface of the conducting sphere of radius B to the distance x.

:

(3) $$E=\int_B^x e\,dx=\rho\frac{I}{2\pi}\int_B^x\frac{1}{x^2}dx=\rho\frac{I}{2\pi}\left[\frac{1}{B}-\frac{1}{x}\right]$$

where: *E= Potential (volts)*
I=Total current (amps)
e=electric field strength (volts)
ρ=soil resistivity (ohm-meter)
B=radius of spherical electrode(meters)

The relationship between electric field strength, voltage, and distance, can be shown graphically, as in Figure 6.

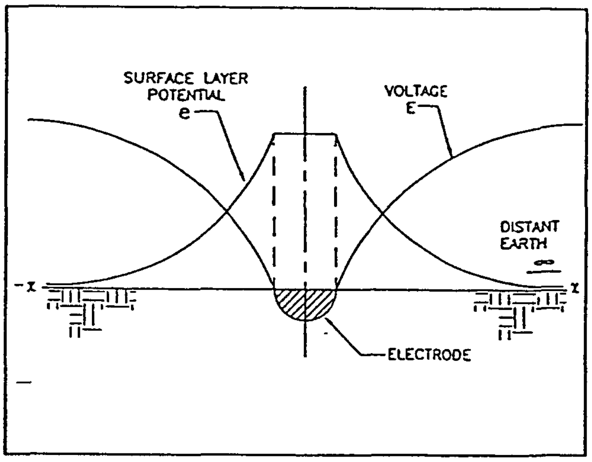

Fig 6 - Potential Versus Distance in Surface Layer

The total voltage between the spherical electrode and *distant earth (*where $x = \infty$) can be derived from equation (3):

(4) $$E=\rho\frac{I}{2\pi B}$$

From this expression, the resistance of the electrode to *distant earth* can be computed:

(5) $$R=\frac{E}{I}=\frac{\rho}{2\pi B}$$

Example:

As a hypothetical example, typical track gauge is 4 feet 8-1/2 inches, or approximately 1.43 meters. We can approximate a ground on the rails by assuming an electrode with radius of 1.43 / 2 = 0.71 meters. For soil resistivity of 100 ohm-meters, the ground resistance of this electrode will be:

$$R=\frac{10^2}{2\pi 0.71}=22.4 \qquad \text{Ohms}$$

In practice, this approximation may represent an abnormal condition where a section of rail has been solidly grounded inadvertently, or perhaps a failure of the rail isolation system.

Choosing the radius of the electrode will determine the resistance to earth of the electrode. If we wanted to represent the direct connection to earth of one failed rail fastener, the effective radius would be approximately one-half the width of the rail.

For a single electrode, the resistance to earth is concentrated in the proximity of the electrode as shown in Figure 6. Indeed, half of the voltage drop caused by the current injection into the grounding electrode would appear within one diameter of the electrode. Earth is a relatively poor conductor with a resistivity about 1 billion times that of copper. The resistance to earth may be imagined to consist of equal thickness concentric spherical shells about the electrode. The inner shell will represent the largest incremental value of resistance, since the resistance is inversely proportional to the distance from the electrode, and will therefore drop the largest voltage. After several electrode diameters, the resistance to *distant earth* becomes negligible for all practical purposes.

Definition: *"Distant earth" may be thought of theoretically as an imaginary sphere an infinite distance from the electrode, and at zero potential*

Flow of Current Between Two Electrodes

In order to explore the relationships between various grounds such as the utility grounding system and the traction electrification negative return system, and in particular between utility ground and the traction power substation ground mat, we are interested in the special case where current flows between two electrodes. It is possible to construct a network using two electrode systems, and this will give us a tool to model a system, by simply knowing the voltage between electrodes, and the resistivity of the soil.

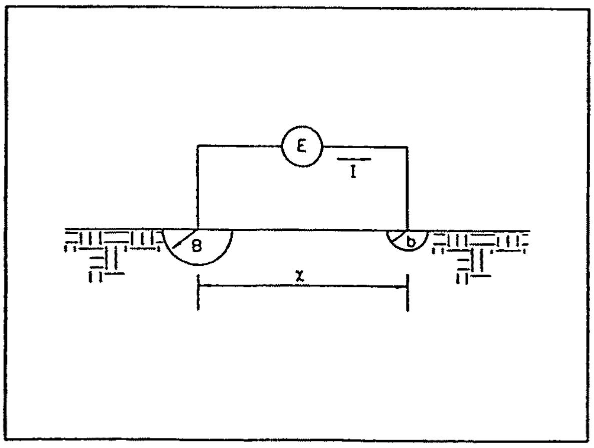

Fig 7 - Two Electrode System

Refer to Figure 7. Assume that we have two spherical electrodes of different radii B and b, each with one hemisphere buried in homogenous earth with uniform resistivity. These electrodes could represent any two points on the rail, a grounded negative return, or a ground on the electric utility.

Definition: *"Sphere of Influence" means an imaginary surface at which the electric field potential surrounding an electrode becomes zero. (For purposes of this paper we will define the sphere of influence to extend to where the field strength has been reduced by 95% from maximum)*

Assume that a voltage is applied such that a current flows into the first electrode, through earth, and returns through the second electrode. Assume also that the two spheres are separated by a distance x, which is chosen to locate the electrodes far enough apart so as to be outside of the *sphere of influence* of each other. At this distance, the voltage E will be independent of the distance x between the electrodes.

By application of equation (3) to both electrodes, an expression may be derived which gives the resistance of the path between the two electrodes.

$$R=\frac{E}{I}=\frac{\rho}{2\pi}\left[\frac{1}{B}+\frac{1}{b}-\frac{2}{x}\right] \tag{6}$$

Note that this equation is not valid if electrodes are arranged in parallel or located within each other's sphere of influence.

Grounded Negative Return Model

One of the models we would like to develop depicts a substation with a grounded negative return bus such as through a diode, and relate that to another ground on the negative system.

The rail-to-earth isolation for modern electric railways is typically tested to 500 ohms per 1000 feet of single direct fixation track under worst case conditions. Under ideal conditions, given dry high resistivity soil, this value can be much larger, in the range of 1000 ohms per 1000 feet of single track or higher. This leakage resistance is usually considered to be distributed throughout the length of the track. These values are achieved through the use of appropriately designed insulating track fasteners. (See Appendix A Table 1 and Table 2 for rail resistances and track-to-earth resistances used in this paper).

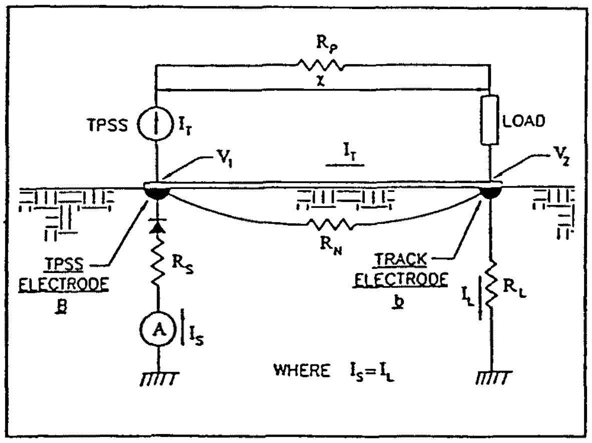

Figure 8 - Grounded Negative Model

Where R_L*=track-to-earth electrode resistance at the load end (to distant earth)*
R_S*=track-to-earth electrode resistance at the source end (to distant earth)*
R_N*=resistance of negative return circuit*

$$I_T >> I_L,\ I_T >> I_S$$

Consider Figure 8, above. Here we define a traction electrification system consisting of a single traction power substation (TPSS), with the return current flowing though the rails of a single direct fixated track. We define the resistance of the negative return to be R_N. We also define a low resistance ground electrode R_L on the track at a distance x from the substation, and the voltage on the track at this point is defined to be V_2. The voltage $V_1=0$ when referenced to the rail, but since we are interested in earth potentials we note that the potential from V_1 to distant earth may not be zero.

The substation negative return bus is intentionally diode grounded by an electrode of resistance R_S, and an ammeter inserted in the grounding lead so that we may measure the current which returns to the TPSS through earth. For our purposes, we assume that both electrodes can be modeled as spheres. Further, we assume that the soil is homogeneous, of constant resistivity, *"distant earth"* is at zero potential, and all current flowing through the rail electrode will return to the substation electrode through the ammeter and the TPSS grounding electrode.

The voltage $V_2 - V_1$ at any point on the track a distance *x* from the TPSS is then the product of rail return current I_T, and the resistance of the single track R_N between the point *x* and the TPSS. This equation can be expressed as follows:

$$(V_2-V_1)=I_TR_N=I_Tr_Nx \tag{7}$$

where r_N is the rail resistance from Table 2 expressed in ohms per meter.

In order to develop an expression for the "stray" current I_S returning to the TPSS from the rail electrode through the ammeter, we can then combine equations 6 and 7, and solve for current I_S

$$I_S=\frac{2\pi(V_2-V_1)}{\rho\left[\frac{1}{B}+\frac{1}{b}-\frac{2}{x}\right]}$$

Note that where the distances between the two electrodes is large enough to be outside of the sphere of influence of either, the term *2/x* becomes negligible. Rewriting the above expression in terms of the train current and resistance of the negative return, this expression becomes:

$$I_S=\frac{2\pi I_TR_N}{\rho\left[\frac{1}{B}+\frac{1}{b}-\frac{2}{x}\right]} \tag{8}$$

The magnitude of leakage (stray) current I_S, can also be expressed as a function of the distance from the substation *x* along the rails:

$$I(x)=\frac{2\pi I_Tr_Nx}{\rho\left[\frac{1}{B}+\frac{1}{b}-\frac{2}{x}\right]} \tag{9}$$

The potential distribution across the surface of the earth caused by stray current leaving one electrode and flowing into the second electrode can be shown to be similar to Figure 9, below:

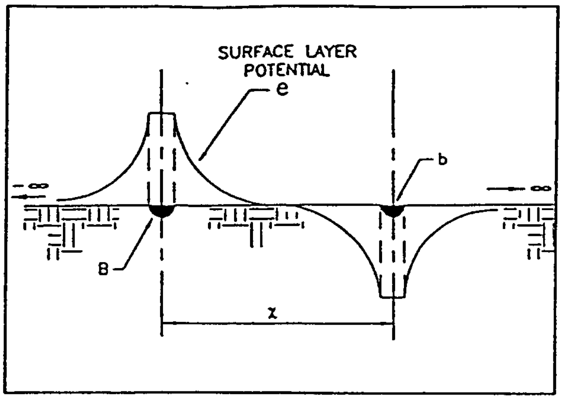

Fig 9 - Surface Potential between Two Electrodes.

The currents flowing between the two electrodes distribute themselves as shown in Figure 10, below:

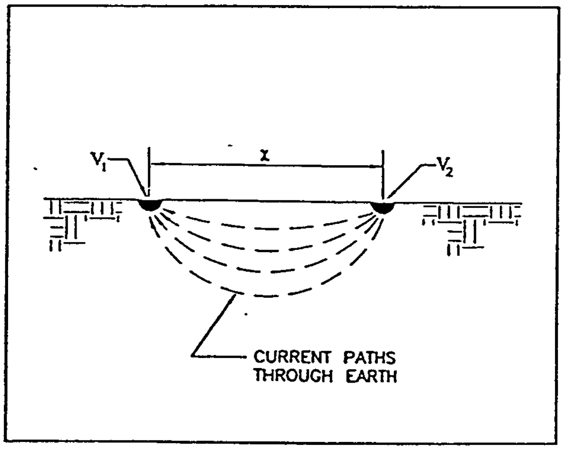

Fig 10 - Current Paths Through Earth Between Electrodes

Example: Given a constant flow of train return current of 1000 amperes through a single track (2 rails), using 115 RE rail with a resistance of 1.55×10^{-5} Ohms/Meter, and a track-to-earth resistance of 500 ohms/1000 ft (304.8 Meter), uniform soil resistivity of 100 Ohm-Meter, a TPSS electrode of radius 10 meters, and a rail electrode radius of 0.1 Meter, what will be the magnitude of the stray current flowing through the ammeter shown in Figure 8?

Solution: We can substituting directly into equation (9) and the solution is:

$$I=\frac{2\pi(1000)(0.0000155)(304.8)}{100\left[\frac{1}{10}+\frac{1}{0.1}-\frac{2}{304.8}\right]}$$

I=0.02939 Ampere

Expanding the use of Spherical Electrodes on the Traction Electrification System

In Part 1 of this paper, we discussed the Basic Stray Current Model, and the Computer Simulation Model. We would now like to expand the concept of using spherical electrodes to model more than two grounded points on the negative return system. The premisses are:

- *The negative return system can be modeled using spherical electrodes to represent connections to earth, either intentional or inadvertent*
- *The flow of current through earth from one grounded node on the track of higher potential to another grounded node on the track of a lower potential may be calculated knowing the potential to distant earth of each point, the resistivity of the soil, and the effective size of each electrode.*
- *Currents may be added by superposition to calculate the total current flowing into or out or nodes on the track.*

Consider Figure 11, below:

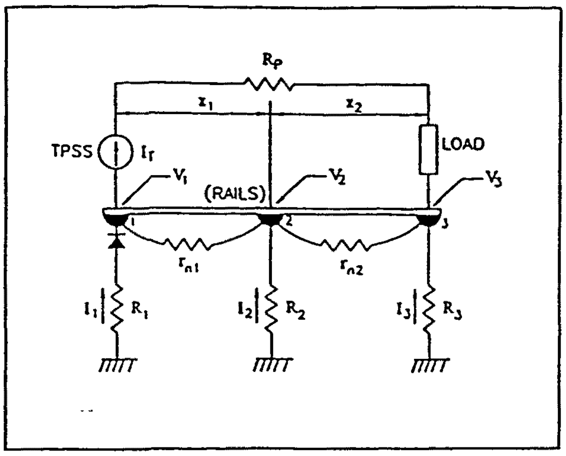

Fig 11- Basic Stray Current Model using Spherical Electrodes

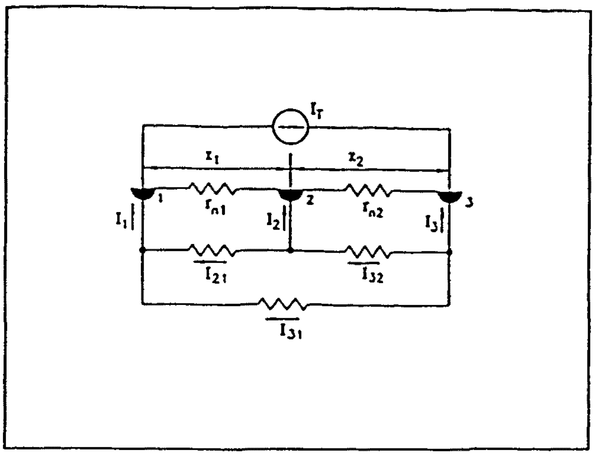

Fig 12 - Nodal Circuit Diagram

Here, we have drawn the circuit, developed from Figure 8, to indicate distant earth as a separate node, and the various nodes associated with the circuit. We have defined paths for current to flow from points on the single track (2 rails) to and from distant earth, which represents connections to ground on the system.

However, we can re-draw the circuit as shown in Figure 12, using only 3 nodes and equation (9), and calculate all the currents flowing through earth among nodes.

For ease in notation, we again label the nodes as 1,2,3, respectively. The current among nodes are given as I_{32}, I_{21}, I_{31}. We may calculate either an exact solution, or an approximate solution. Since the expected magnitude of the train current is expected to be 1000- 10,000 times greater than the currents flowing through earth, for simplicity and approximate analysis we may neglect subtracting the stray currents from the train current at the node junctions, and treat I_T as a constant. The resulting circuit is shown in Figure 12, below:

Note that in this simplified diagram, distant earth is not shown, but has been accounted for in the development of the equations. For a three node network we can represent each node as a spherical earth electrode, and calculate the stray currents flowing between each pair of nodes using equation (9):

$$I_{32}=\frac{2\pi I r_n x_2}{\rho\left[\frac{1}{b_3}+\frac{1}{b_2}-\frac{2}{x_2}\right]} \tag{10A}$$

$$I_{21}=\frac{2\pi I r_n x_1}{\rho\left[\frac{1}{b_2}+\frac{1}{b_1}-\frac{2}{x_1}\right]} \tag{10B}$$

$$I_{31}=\frac{2\pi I r_n (x_1+x_2)}{\rho\left[\frac{1}{b_3}+\frac{1}{b_1}-\frac{2}{(x_1+x_2)}\right]} \tag{10C}$$

Where:

b_1, b_2, b_3 = *radius of each node electrode*

respectively (meters)
I_t*=Total Train Current (Amps)*
r_n*=resistance of rail between points(ohms)*
x=distance between nodes (meters)

By using superposition and Kirchoff's laws, we can find the currents flowing into or out of each node:

$$I_1=I_{21}+I_{31} \tag{11A}$$

$$I_2=I_{32}-I_{21} \tag{11B}$$

$$I_3=I_{32}+I_{31} \tag{11C}$$

This approach permits easy exploration of topics such as determining the magnitudes of stray currents caused by grounding the negative return through a diode. We can also explore whether a separate dc grounding mat should be used to ground the negative bus, and if so, what separation through ground will be sufficient to attenuate flow of current from the dc system to the electric utility grounding system.

Grounding the Electric Utility to the Traction Power Substation Negative Return

We would like to discuss one special condition where the Traction Power Substation features a single ground bus and ground mat, and both the serving electric utility and the traction power substation negative return are grounded to this same mat. Consider Figure 13, below:

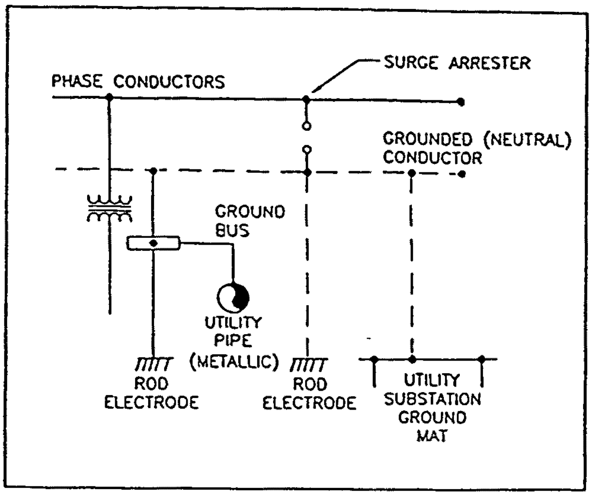

Fig 13 - Electric Utility Grounding System

The electric utility grounding system is a multi-point grounded system. The utility distribution network provides power to many individual electrical services or substations, each of which has at least one grounding electrode. Within a residence or industrial or commercial building, the electric grounding electrode is connected to the water pipe, and structural steel and even concrete reinforcing steel, if present. Most modern distribution three phase medium voltage systems carry a grounded conductor with the phase conductors, often as a concentric neutral wound around each phase conductor. The grounded conductor provides a low impedance return path for the circuit's ground fault protective device. Since most metallic electrical appliances within a building or residences are also grounded to this system, it also provides some measure of protection to people against electric shock from potential differences.

The electric utility multi-point grounded system provides a major problem for electric railroads if there is a connection from the substation negative return to the utility ground, thus effectively establishes another negative return system in parallel with the tracks and in direct contact with other underground metallic structures. Modern corrosion control methods seek to minimize possible potentials between the tracks and underground utilities by using track insulating systems, and isolating metallic underground utilities by coating, or changing materials from metallic, to non-metallic. In some cases, utilities will choose to protect their metallic systems by passive means, such as sacrificial anodes, or active means, such as impressed current.

The electric utility system does not lend itself easily to modeling, since by definition, its grounding electrodes are randomly placed, and tied together through grounded conductors and system neutral conductors, and these are in turn tied to underground piping. For this reason, we need to approach this problem in a qualitative way.

For a moment, let us return to the two electrode model. We know that a difference in potential between two points on the surface of the earth will cause a flow of current through earth from a point of higher potential to lower potential. We also know that in order for one electrode to be considered "isolated" from the other, each must be located outside of the others sphere of influence. When we tie the negative return to the electric utility grounding system, either directly and solidly by using a conductor, or indirectly, by locating the electric utility ground within the sphere of influence of the dc ground mat, we may expect increased stray current to flow since the electric utility ground system is widely distributed and well within the sphere of influence of many underground metallic structures . Worse, since the utility return is now in parallel with the negative return, we may expect that under certain conditions not only will the utility carry stray current from the dc traction system, but the rails may carry currents generated by the utility system, and this may happen in a way that is difficult to predict or analyze. It is possible that utility currents flowing over the rails can also cause abnormalities in the train protection signal system, which is a fundamental safety concern.

In conclusion, it appears qualitatively desirable that the design engineer isolate the utility ground system from the negative return as far as practical by not grounding the utility neutral to the negative return, and by not placing the dc grounding electrode within the sphere of influence of the utility grounding system. In addition, care must be taken if the utility neutral is connected to the substation ac ground mat, to isolate the dc grounding electrode by locating it outside the sphere of influence of the ac mat.

CONCLUSIONS:

One common misconception we have encountered is a belief that there is a relationship between current flowing through earth between electrodes, and the distance apart the electrodes are spaced. We can see that the magnitude of current flowing between two electrode points is a function of soil resistivity, the potential between the electrodes, and the size of the electrodes , as long as each electrode is located out of the sphere of influence of the other. Space does not permit discussion in this paper of all aspects of dc traction power grounding. However, further effort is needed to explore related topics: types of grounding systems and traction electrification grounding system design philosophy, lightning arrester grounding, stray current monitoring systems, track-to-earth monitoring and protection, ground fault sensing and protection and the use of high speed circuit breakers for mitigating the effects of touch and step potentials,.

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BIOGRAPHICAL SKETCHES

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APPENDIX A

Rail-to-Earth Resistance, Rail Resistance, and Average Soil Resistivity:

Track Type	English Units	Metric Units
Direct Fixation Single Track (2 Rails)	500 Ohms/1000 ft	1.5 x 10^5 Ohms/Meter
Direct Fixation Double Track (4 Rails)	250 Ohms/1000 ft	0.75 x 10^5 Ohms/Meter
Embedded (Paved) Double Track (4 Rails)	100 Ohms/1000 ft	0.3 x 10^5 Ohms/Meter
Timber Tie & Ballast Double Track (4 Rails)	50 Ohms/1000 ft	0.15 x 10^5 Ohms/Meter

Table 1: Track to Earth Resistance

Rail Type	English Units	Metric Units
Single Rail (New)	0.05 Ohms/mile	3.1 x 10^{-5} Ohms/Meter
Single Track (New)	0.025 Ohms/mile	1.55 x 10^{-5} Ohms/Meter

Table 2: Resistance of 115 RE Rail

Type of Soil	ρ, Ohm-meters
Wet Organic Soil	10
Moist Soil	10^2
Dry Soil	10^3
Bed rock	10^4

Table 3: Average Resistivity of the Soil

APPENDIX B

Factors Limiting Uniform Soil Resistivity

Throughout this paper we have assumed uniform soil resistivity as a basis for our mathematical models, which implies homogenous composition of the soil. Such is not the case in the real world. The resistivity of a single soil type varies with its composition - whether it is clay, sandy, or loamy (see Table 3), and with how various types of soil are distributed throughout the earth. The geologic strata we find in nature are likely to vary widely, not only over the surface of the earth, but also in depth. Consider the following Figure B-1, taken directly from IEEE 80-1986[2], below, which shows the great variance in soil types in a typical geographical area:

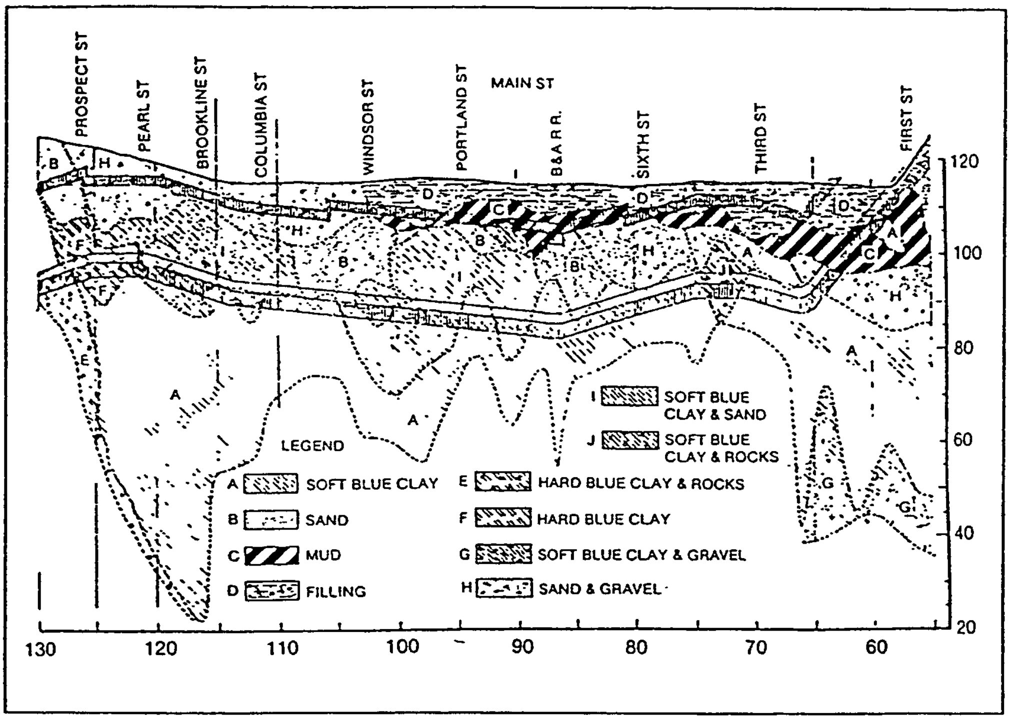

Figure B-1 Subsoil Strata under Main Street, Cambridge, Massachusetts

The soil resistivity of a particular sample depends not only upon the soil composition, but with the moisture content, temperature, humidity, and chemical composition. Some of these factors will vary with weather conditions. Hence, taken together, these limiting factors suggest that rigorous, precise, mathematical analysis of how currents flow in earth over large areas is not practical, nor would it necessarily result in a high degree of accuracy. It follows that such an analysis might also not be economically feasible and justify the intense labor required. It does suggest that a less rigorous analytical approach using abbreviated mathematical models coupled with data from a soil resistivity

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[2] Portions of this discussion and accompanying figures are taken directly from IEEE Std 80 Appendix H, and reprinted here with permission. Copyright 1986 IEEE. All rights reserved.

field investigation together could result in the most practical and cost effective analysis for large geographical areas, such as a rail line. It also suggests that when calculating much smaller site-specific problems related to earth currents, such as sizing substation ground mats, that the soil resistivity be determined from local site investigation.

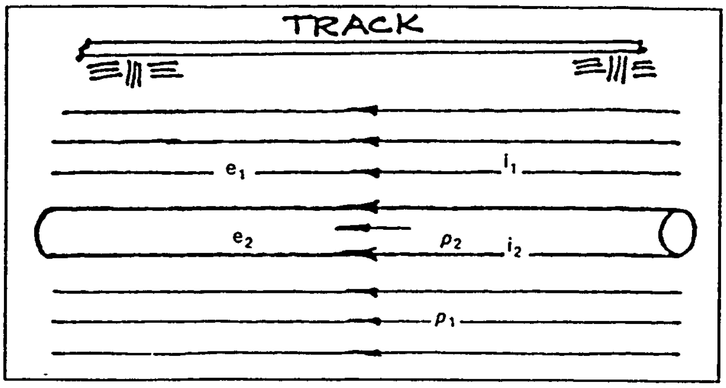

Figure B-2: Long Pipe in Extended Ground Field

We would like to touch very briefly upon one other constraint affecting earth calculations - underground metallic utilities. Borrowing again from IEEE 80[3], Figures B-2 and B-3 depict a long pipe buried in an extended ground field, and a short pipe buried in an extended ground field. We have added the track to the figures to establish orientation of the track to the electric field. Note that a buried pipeline parallel to the track establishes a region of conductivity, and this is depicted as a different resistivity from surrounding earth, adding a complexity to calculating underground currents. When the pipe becomes short or irregular, the complexity increases as the flow of current and electric potential field is distorted.

In summary, when making calculations involving underground currents, be aware that there are limiting factors which restrict the degree of accuracy which may be obtained by calculations.

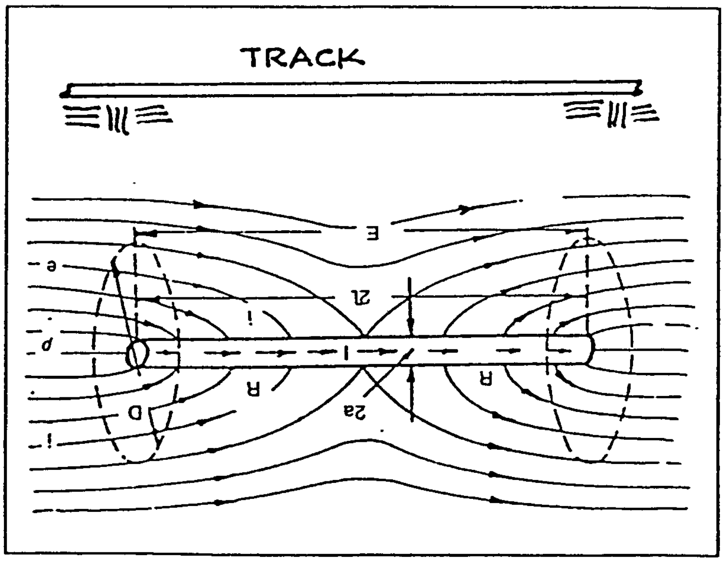

Figure B-3: Short Pipe in Extended Ground Field

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SOLATION AND GROUNDING SOLUTIONS N CATHODICALLY PROTECTED SYSTEMS

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NTRODUCTION

athodic protection requires DC isolation from ground for the structure being protected. Yet, at the me time, safety concerns exist regarding exposure to AC faults, AC induced voltage, lightning, or her electrical disturbances, which require solid grounding. Technology advances have led to the sign of solid-state AC grounding/DC blocking devices, which can meet both requirements multaneously. This technology has eliminated maintenance requirements, as compared to liquid-filled larization cells. Common applications include over-voltage protection of insulated joints, mitigation induced AC voltage, grounding AC power system faults, blocking stray DC current, and isolating ctrical equipment on CP systems, such as motor-operated valves. The technology has been applied to elines, tanks, pipe-type transmission power cable casings, lead sheath cable casings, and other thodically protected equipment. These applications are discussed in greater detail, with regard to ety requirements, codes, proper electrical ratings of devices, and resulting improvements in the hodic protection system.

PLICATION OVERVIEW

thodic protection systems commonly have dual requirements, which are in conflict. The DC isolation m ground, required for a cathodic protection voltage to be impressed on a structure, is achieved ough the use of pipeline coatings, insulated joints, and a reduction or elimination of solid metallic nections to ground. This practice increases the resistance of the structure relative to earth, imizing the current drain on the cathodic protection system, which is typically a rectifier or rificial anode arrangement. However, the improvement in the DC cathodic protection system for the poses of corrosion reduction can, apart from other actions, create unsafe situations for personnel and ipment. As pipelines and other cathodically protected structures may contain electrically powered ipment, or be in the vicinity of electrical transmission or distribution service, the structure may have osure to electrical disturbances. In addition, lightning may pose a risk to the installation. Touch and potentials, established during lightning and AC power system faults, can expose personnel to unsafe tages, unless these issues are addressed in the design of the system. Remedial action can be taken g bonding, grounding, and AC voltage mitigation techniques, which will be described.

these needs may conflict with the DC isolation required for cathodic protection, AC grounding and blocking devices have been introduced to address both issues simultaneously. The solid-state design he present technology allows for a high DC impedance to be established between the two connected nts, typically between a pipeline and ground or across an insulated joint, keeping the cathodic ection potential intact. At the same time, the device appears as a low impedance path to alternating current and higher frequencies, providing a grounding or bonding path for undesirable currents, and thereby keeping the voltage to a low level.

OVER-VOLTAGE EFFECTS

Over-voltage protection must deal with several electrical phenomena. These include lightning, induced AC voltage, and voltage caused by the flow of AC fault current. Each of these situations requires a different protection device rating, and imposes unique system problems when remediation is called for. The effects of over-voltage upon a structure can include coatings puncture, dielectric insulation tracking and breakdown, equipment failure, fuel ignition and explosion, and personnel injury or death.

Over-voltage can be addressed by eliminating large voltage differences between points of concern. Such locations might be:

- At worker contact points
- Across insulated flanges
- From pipe to ground
- Between different grounding systems
- In lengths of conductors

Benefits result from a proper installation designed to deal with over-voltage situations. The most obvious addresses the immediate safety concerns for personnel. Other results might be the improvement in cathodic protection potentials and a reduction in CP current required. These come from the high DC impedance provided by the solid-state devices. In cases where grounding of electrical equipment is required by code, such as at a motor-operated valve, a third-party listed device such as the PCR provides AC grounding while blocking DC current from the CP system. Finally, several undesirable over-voltage problems can be addressed in a single installation in some cases. An example would be the need for protection of insulated joints, in a location where induced AC voltage is present. Protecting the insulated joint using a solid-state AC grounding/DC isolating device would also provide induced voltage mitigation while keeping the CP voltage unaffected.

LIGHTNING VS. AC CURRENT, AND EFFECTS

A product that provides over-voltage protection supplies a means for conduction when a voltage beyond a certain value is reached. Upon reaching this conduction state, a more important factor enters, which is the current rating of the device. Many over-voltage protection devices do not have an appropriate current rating for the situation where they are located. Such a mismatch can result in conductors or the device failing as an open circuit, with possible arcing, and the loss of future over-voltage protection. Solid-state devices have the benefit of a fail-safe nature, providing current handling capability well in excess of the rating while remaining as a short circuit.

Lightning

Lightning is characterized by a fast-rising waveform, with a decay period. Industry standards for lightning surge current describe this as an "8 x 20 microsecond" waveform, providing a rise time of 8 roseconds to the peak value, and a 20 microsecond decay from peak value to one-half of peak. ile the amplitude of a lightning surge may be high, the duration is in the range of millionths to usandths of a second.

htning Effect Due to Lead Length

ghtning surge can have unanticipated effects on what appears to be a properly designed over-voltage ection system. Due to the inductance of the surge current path, which mainly comes from the length he leads, a large voltage difference can develop across the points to be protected. Lead length can uce a more significant voltage than the threshold voltage of the protective device. If this total value excess of the coating or insulation joint rating, tracking, arcing, or puncture can occur. As leads can lop several thousand volts per foot of length under moderate surge current values, the total installed th should be limited to the minimum possible. For reference, lead diameter does not have a notable t on the inductance value, while lead length contributes overwhelmingly.

ower Effects

ower delivery systems can have several effects on cathodically protected structures. One common t is the presence of induced AC voltage on an isolated structure. Typically found on pipelines in a non right-of-way with electric transmission lines, induced AC voltage can reach levels that require ation. A device that provides AC grounding and simultaneous DC isolation can address this issue ut effect on the CP system.

C power system fault is a significant event that requires protection for affected CP structures. g for AC fault current is the primary concern, a value which dictates the short-term AC ampacity of tection device. While the lead length issue mentioned above regarding lightning surge current is n issue for handling AC fault current, the conductor ampacity (and therefore diameter) should be priately rated.

ICATIONS

ted Joint Over-voltage Protection

ted joints are common on major pipeline systems and tank farms for separation of different CP ns, isolating separately owned pipeline segments, and limiting undesirable electrical influences ower systems. Over-voltage protection of these insulated joints is important for preventing tion puncture, air flashover, metal damage, or pipeline product ignition. The joint assembly as a has an associated minimum breakdown voltage that should be known. Any protective device across the joint needs to have a breakdown or threshold voltage that is lower than the voltage ated with insulated joint failure. Not only is over-voltage protection of the insulated joint le, but a DC blocking/AC conducting device can provide other benefits at this location. When tion of induced AC voltage is of interest, the insulated joint may separate the cathodically ted and AC affected part of the pipeline from the grounded segment, perhaps in a metering or tion station. A solid-state device can provide a conduction path for the induced AC current, around the insulated joint, bonding it to a grounding system for dissipation. Simultaneously, the cathodic protection voltage has been maintained across the joint, with no loss of system performance.

Ratings of interest for this application are the lightning surge current rating, and the AC fault current rating. Other considerations are the blocking level needed, and the AC induced current at this point, if present.

AC Voltage Mitigation

Pipelines in the general vicinity of power lines can be affected by capacitive, inductive and conductive interference.[1] Detrimental effects such as excessive step and touch potentials, and pipeline coating, insulated joint, and steel damage can result. The presence of induced voltage also indicates that AC fault current exposure exists. General industry guidelines are available to direct the user to commonly accepted characteristics and limits of these electrical hazards.[2] Providing an AC mitigation system, which can include a solid-state AC conduction/DC isolation device, can reduce those risks.[3] Such a system is usually designed using software analysis tools for modeling the system.

Establishing a low impedance AC conduction path for steady-state induced AC current can lower the induced voltage to acceptable levels. While the solid-state device is in the DC blocking mode, it has a 60Hz AC impedance of typically 5 milliohms to 250 milliohms. When the device is triggered on, the impedance of the device becomes negligible, creating a short-circuit between the pipeline and grounding system. The total AC impedance of the grounding circuit clearly includes the grounding electrode, which must have a suitably low value for the overall installation to be effective.

Various methods of electrode layout are possible, but one interesting method is accomplished using gradient control wires, which are run continuously on either side of the pipeline.[1,3] A solid-state device connects the gradient control wires, commonly zinc ribbon or copper wire, to the pipeline, and performs a DC blocking function while making the pipeline and wires appear AC continuous. The zinc ribbon in this case is not acting as a sacrificial anode, but strictly as an AC grounding system. In this arrangement, a cathodic protection rectifier provides the protection current to the pipe. The gradient control wire method provides an additional benefit - it brings the potential of the soil close to that of the pipe all along the length, minimizing the step and touch potentials for personnel to lower levels, and more uniformly, than other methods.

Other grounding arrangements are possible: vertical rods and deep well systems, or utilizing existing grounding systems. For sites where an insulated joint separates a pipeline section from a grounded section, connecting the solid-state DC blocking/AC conducting device across the joint can conduct induced AC current to ground.

The main ratings of interest for this application are the AC fault current available, and the steady-state induced AC current for the point of connection. The AC fault current value at the site can be determined or estimated by taking the maximum available current that the power utility provides, and refining the value at the pipeline using the modeling techniques mentioned above, usually performed by consulting engineers. The induced AC current can be determined by temporarily bonding the pipe to ground and asuring the AC current using a clamp-on ammeter. Note that this value will vary along the length of pipeline, as it is affected by numerous factors.

ating Electrical Grounds Required by Code

conflict of simultaneous AC grounding and DC isolation is never more apparent than at sites where trical equipment is located on a cathodically protected system. Electrical codes require solid nding of the powered equipment, but this bond can bring CP potentials in the vicinity to ceptable levels. In the U.S., for example, section 250 of the ANSI/NFPA-70, the National Electric e, describes the grounding requirement on secondary electrical systems.(1) Additionally, section 6(e) allows for the use of third-party listed products to block "undesirable DC ground currents" in connections. An example of such a product is the Polarization Cell Replacement (PCR), a UL-CSA-listed device. The typical case is where a PCR is placed in the grounding lead of a motor-ated valve for DC isolation and AC fault grounding. Reference Figure 1 for an electrical schematic s installation.

r grounding requirements exist that complicate matters regarding cathodic protection. Power es bond their grounded primary neutral to the customer's secondary neutral, which is grounded at rvice entrance panel to the station grounding system. This is governed by the National Electric y Code (NESC) in the U.S., which defines power utility practices. For cases where DC isolation of ic electrical equipment is not easily attained, due to numerous metallic bonds between the CP n and ground, a suitable alternative is primary-to-secondary isolation. The NESC allows for on between the primary and secondary neutrals, and placement of a PCR in this location provides solation of the entire site from the power utility grounding system, which is extensive. This gement would be installed by the power utility that serves the customer who desires isolation. ence Figure 2 for an electrical schematic of this installation.

ding Power Cables for AC Fault Current

utilities utilize underground distribution and transmission cables for serving concentrated areas. n cable construction generally requires corrosion protection of the exposed casing or sheath. Two les are oil-filled pipe-type transmission cable casings, made of steel, and the outer lead sheath of xtruded cables. Both have corrosion concerns, and therefore may be cathodically protected. Due need for a DC bias from a CP system, the casing or sheath is isolated from ground. However, ites have significant AC fault current exposure that must be addressed. For phase-to-ground thousands or ten-thousands of amperes will flow, and a suitably rated AC grounding system is for conduction of this over-current. A solid-state AC grounding/DC blocking device placed n the pipe or casing and the grounding system can direct this heavy current flow safely, until the

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250-2(d), Performance of Fault Current Path:
lt current path shall be permanent and electrically continuous, shall be capable of safely carrying the maximum fault be imposed on it, and shall have sufficiently low impedance to facilitate the operation of overcurrent devices under ditions. The earth shall not be used as the sole equipment grounding conductor or fault current path."

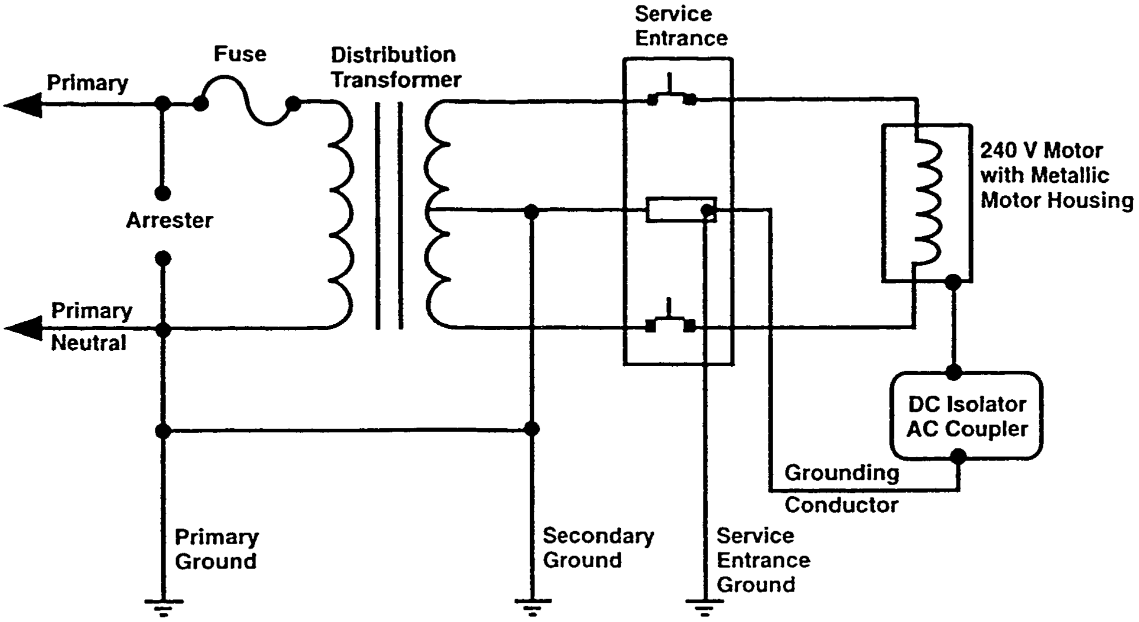

FIGURE 1 - DC isolation from primary and secondary grounding systems

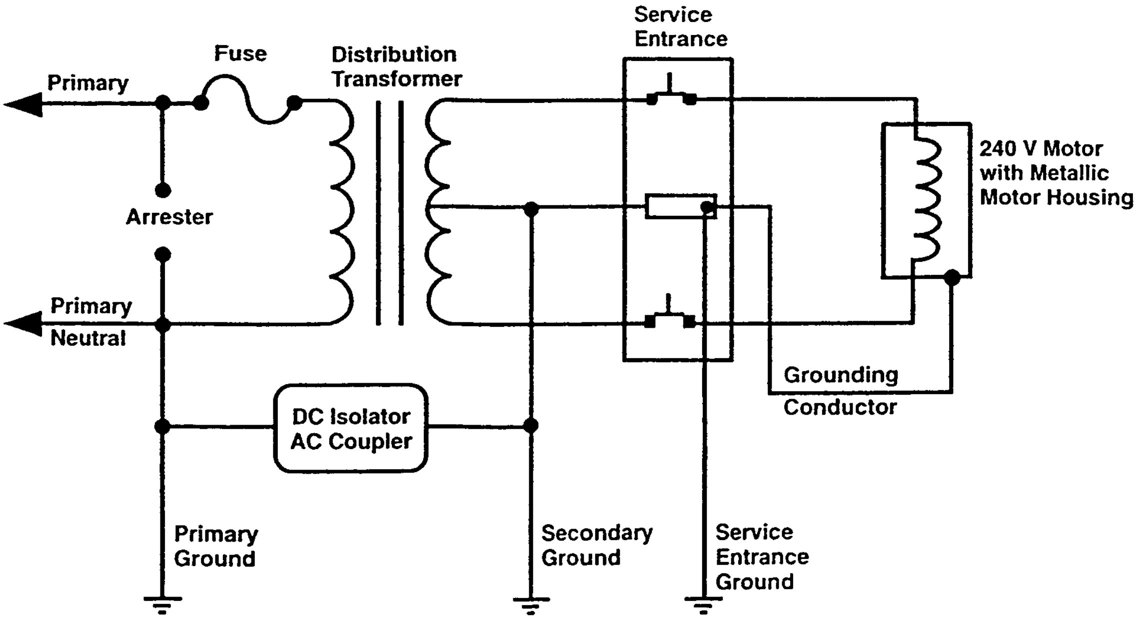

FIGURE 2 - DC isolation from primary grounding system only

lity power circuit breaker operates, typically within 3 to 15 cycles. Devices are typically located at h end of a cable run, where the cable enters a substation, tying the casing or sheath to the station unding grid.

quirements of a DC isolating/AC conducting device in this location are similar to the AC Voltage tigation discussion above, however certain conditions can be more extreme. As described, the AC lt current magnitude is usually much higher for grounding utility cables, and the steady-state AC rent coupled to the casing or sheath can be higher and more variable as well. This is especially arent as utility loads change or the utility power system is reconfigured. Additional requirements in an settings may be for the blocking device to keep stray DC current off of the cable systems. Higher shold voltages are needed for this situation, something that is easily accomplished with the flexible gn of the solid-state products.

Past arrangements of protective schemes for power cables included resistor-rectifier binations, or use of polarization cells, now commonly being replaced with Isolator/Surge Protectors). Resistor-rectifier systems consisted of a rectifier connected to the pipe casing, with a heavy tor connected between the pipe and station grounding system. The voltage drop across the resistor ided the CP potential, as well as acting as an AC grounding path for faults or induced current. lems with this design included balancing the need for a low enough resistance for limiting the ge during an AC fault, while having a high enough resistance to create a suitable voltage drop for dic protection. In addition, the copper station grounding grid degrades as current circulates in this Many of these sites are being converted to a rectifier with a solid-state ISP connecting between the and station ground grid. High AC fault current conduction capability and improved DC isolation t from this type of installation.

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ELECTROLYSIS FROM RAILWAY CURRENTS

By Arthur Vaughan Abbott, C E.

August 1899

SEVERAL years ago much excitement and apprehension were aroused by the announcement that the underground metallic structures in many cities were menaced with destruction from the corrosive action of electric street railway currents. The extensive pipe plants of gas and water works were, it was averred, doomed to immediate disintegration, with the inevitable result that the inhabitants would be drowned, if they were not previously blown up. The lead sheaths of electric cables that, after a stubborn fight, had been torn from unsightly pole lines and thrust into subterranean conduits, were discovered to be not only in particular danger, but, when perforated, would furnish the igniting spark that would precipitate the general holocaust. The illustrated scientific press teemed with pictures of pipes in the most advanced stages of decomposition, and the opponents of the "deadly trolley" were filled with satisfaction at the efficiency of the new casus belli. Indeed, it seemed as if, in spite of its generally acknowledged convenience and utility, "the broomstick train" was doomed, and must, with the witch who hauled it, be relegated to the past. But the inevitable reaction ensued. All the pipe systems did not immediately go to pieces, but, on the contrary, evidence from one town where the gas mains had been severely exposed, showed little injury, so that the railway people took heart of grace, and, emerging from the odium with which the "anti-trolleyites" had covered them, serenely proceeded on their way.

At present comparatively little is heard of electrolysis, but still electric currents from hundreds of power stations steadily creep through the earth, and while they may not inflict the predicted wholesale destruction, they are far from being harmless. Unless carefully controlled, they may, indeed, inflict considerable injury.

When electricity passes from place to place, a portion is absorbed in the bodies which form its path. In solids this dissipated energy is transformed into heat and expended, sometimes disastrously, in raising the temperature of the conductor, while in most liquids it is chiefly occupied in decomposing the fluid into its component chemical elements. Thus, if water form a portion of the circuit, it will be separated into oxygen and hydrogen, the oxygen appearing at the positive pole, or anode, and the hydrogen at the negative pole, or cathode. The elemental gases only make their appearance at the surfaces of the conductors extending into the liquid, and, at the instant of decomposition, seem to be endowed with extraordinary activity, readily corroding all but the most resisting substances. This process of decomposing a fluid conductor, or electrolyte, is termed electrolysis, and. used in the art of electroplating, ante dating a few months the introduction of the telegraph, is claimed to be the first practical application of electricity.

Like fire, electricity is a good servant, but a bad master, and so long as it was usefully employed in coating spoons and forks, electrolysis proved itself a most valuable discovery. With the advent of the electric railway, however, a loophole of escape appeared, and the lightning that had been harnessed to deposit metals, carry messages, and drag cars, relieved from a confining path, wandered into the ground with mischievous intent, for in every trolley road electrical engineers had set up a gigantic electrolytic cell. With its engines and dynamos, the power station furnishes an almost inexhaustible supply of current that, passing through the trolley wire and car motor to the rails as one pole, finds in the moist earth a conducting fluid, and an opposite pole in the sundry metallic structures it may encounter on its return.

In an electrolytic cell corrosive action is confined to the anode. If the arrangement of railways is such as to make the rails the positive pole, disintegration would be confined to this portion of the circuit and cause dissatisfaction only to the railway owners. Such would be the case provided all subterranean metallic structures presented a path of 'less resistance than any other route. They would then be universally electro-negative, and no damage could result; but this is not the condition found in practice. A pipe line may parallel a track and then branch off. The joints between pipe lengths may be of comparatively high resistance, and at all such places electricity will seek the earth, with ensuing corrosion. So, while there cannot be the slightest ground for opposition on the score of possible injury to putting an indefinite amount of electricity into the underground systems, there is the most serious objection to its getting out again, excepting in so orderly a manner as never to make spots which are electro-positive, and the real problem is,- How shall all underground metallic plants be always maintained electro-negative?

Expedients galore have been proposed as solutions. To provide a complete metallic circuit, and, by thus preventing any current from entering the ground, secure complete immunity, is at first the most obvious and most radical proposition, but one which necessarily inflicts considerable hardship on railway interests. Immense sums are invested in existing single-trolley roads using the ground as a return circuit. Tō remodel these, to operate by some form of insulated circuit, would require an enormous outlay, regardless of mechanical difficulties. Certainly from the railway manager's point of view, the double-trolley is impracticable, evidence of which is the survival of the single-trolley which has displaced the older metallic system, with which all early roads were equipped, and it is urged that, as electrolytic action can be confined to relatively small areas, it is unjust to require the reconstruction of entire railway systems, until it is shown that the danger spots cannot be suitably protected.

The alternating current has been held to provide a perfect relief and to obviate the constructive difficulties of the double-trolley; but this proposition, in avoiding a mechanical Scylla, steers into an electrical Charybdis, for there are practically no alternating current motors suitable for street railway work, nor, from the present outlook, is the advent of such apparatus likely. It seems hardly safe to assert that corrosive action would, by such substitution, be always entirely averted. Ordinarily chemical decomposition does not appear to attend the passage of alternating currents through liquid conductors, but the numerous devices for producing unidirectional currents from alternating circuits by the use of electrolytic cells, arouses a doubt as to the thoroughness of the promised relief.

Railways on the three-wire system, with the earth as the neutral conductor, furnish a solution particularly attractive to the railway manager, for under cover of an endeavour to prevent corrosion, the voltage may be doubled, and, theoretically, the cost of the feeder system reduced to one-fourth, while the earth is relieved of any currents but those which might pass laterally between the rails. But the three-wire system can be applied only to double-track roads, and excessive earth currents can be avoided only when both tracks are close to each other, and when the demands of the cars upon opposite portions exactly balance, - conditions that in practice can never, even approximately, be continuously realized. The hazard of two naked wires, differing by 1000 volts in potential, is ncurred, and the currents in the earth as a neutral conductor constantly shift over the whole rail system, following changes in car load, rendering the location of danger areas difficult, if not impossible. Yet in favourably arranged roads, and with intelligent design, this plan may prove valuable.

To obviate the mechanical difficulties of the double-rolley, it has been proposed to erect a complete feeder system of both outgoing and return conductors, properly nsulated, and to connect the track at frequent intervals with the return wires, in such a manner that all paths to the station should be of equal resistance. The dynamos would be joined to proper feeder conductors, and no grounds allowed. Then the rails would carry current merely between any adjacent connections to the feeder system, and by making these sufficiently frequent, and by paying attention to good rail-bonding and adequate insulation, earth leakage may be completely avoided. While this plan s efficacious in preventing electrolysis, the cost of the onductor system is quadrupled for the same fall of potential, and there is a constant additional expense for the energy dissipated in the compensating resistance. This it is possible to reduce to any desired medium, but only by again increasing the expenditure for the conductors, which on any but very short roads would soon become prohibitive.

Such have been the principal plans for preventing electrolysis by keeping railway currents away from subterranean metallic structures; but as no harm can accrue from the entrance or passage of electricity, and as corrosion occurs only when the current leaves the metal for the earth, it seems pertinent to concentrate attention upon such points with a view to providing, if possible, efficient local protection. The first step is such a study of the territory as will enable its electrical condition to be ascertained. This information is best gained by an electrical survey. Where the area to be examined is small and the railway and underground systems simple, the early method of making voltmeter measurements between the water hydrants, lamp-posts and the rails and adjacent ground usually indicates with sufficient accuracy the points in the pipe systems which are positive to earth; but where the territories extensive, and railway and. underground systems are complicated, more comprehensive measurements are advantageous, and a thorough knowledge is best secured by drawing upon a map of the city in question a series of equipotential lines giving electrical contours. By selecting some desirable central point as a datum and taking advantage of the network of conductors that cover all towns, as electric light and power circuits, telegraph, telephone and fire alarm lines, the difference of potential between the datum and a sufficient number of points may be rapidly measured. With the positive poles of station dynamos connected to the trolley wire, each station becomes the centre of a negative area that gradually diminishes in intensity. If the ground were of uniform conductivity, and if the tracks radiated equally in all directions, the equipotential curves would be a series of concentric circles with each station for a centre; but chiefly owing to eccentricities in the track system, the curves are expanded into irregular ellipses, the longer axes of which are essentially parallel to the rails. Proceeding from each station the potential gradually decreases to zero, and then increases to a positive maximum, so that the electrical condition may be compared to a rolling country in which each station occupies a deep hollow and is surrounded by a series of circular hills.

It is also desirable, with a view to estimating the probable amount of electrolysis, to determine the changes in earth potential that are likely to occur from time to time. This information is easily secured by a series of consecutive observations between convenient points which may be plotted as a curve showing the time-potential relation. Given an equipotential map, it is easy to determine the condition of the earth in any direction, and so ascertain probable danger points. If an imaginary plane be passed through the earth, its intersection with the equipotential curves will give a series of points forming a curve that represents the electrical condition along the plane.

Metallic structures that run parallel to equipotential curves lie in regions of constant potential and are unaffected; but if they intersect different equipotential lines, they will pass through territory of differing potential and the number of curves intersected in a given distance, or the steepness of the electrical gradient, is a measure of the probable tendency for the current to enter or leave the pipe line. Wherever the earth potential is falling or becoming more and more negative, the metallic structures will tend to be more and more electro-positive, for the current will endeavour to flow toward regions of least potential, and, conversely, in areas of rising potential, the pipe lines will tend to be electro-negative.

When railway electrolysis was first discovered, sweeping assertions were made as to the omnivorousness of the current in attacking, without respect, all metallic street structures, and laboratory experiments were cited to show that most minute differences of potential were sufficient to excite action. Practical experience has not fully sustained these early gloomy prophecies; contrarywise, it has been demonstrated that lead is the most sensitive metal, is attacked by the smallest difference of potential, and yields most readily and rapidly to corrosion. Wrought iron comes next, while cast iron, particularly those varieties that contain large amounts of carbon and silicon, known as white cast iron, are so little affected as to be almost exempt. The lead service pipes, therefore, from the water mains, and the sheaths of underground electric cables will be the first and chief sufferers. The wrought iron gas and water services, and the wrought iron pipes of the newer gas companies stand next, while the cast iron mains of the older installations, particularly those pipes made of chill iron, will practically escape injury.

The degree and rapidity of the corrosive action depends upon the quantity of current flowing, and the nature of the soluble salts contained in the surrounding soil. Chlorides or nitrates from the street wash in a clayey or loamy soil favour action, while in clean, dry sand, corrosion is a minimum. If corrosion were uniformly distributed over the entire surface of an exposed pipe, a measurement of the current and an analysis of the soil would enable a fairly accurate prediction as to the probable rate of injury, but as disintegration always proceeds by pitting, the damage is concentrated on particular spots, and the metal is perforated with comparative rapidity. As lead is most rapidly attacked, it is easy to test the probable maximum rate of action at any place by, putting weighed test pieces of sheet lead in the street manholes and reweighing them after a lapse of time.

The greatest economy in a local protecting system is attained by making it as small as possible, and the system is a minimum under the following three conditions:-

1. The danger areas must be reduced to their least dimension.
2. They must be brought as close as possible to the power station.
3. The current escaping from electro-positive points must be reduced to a minimum.

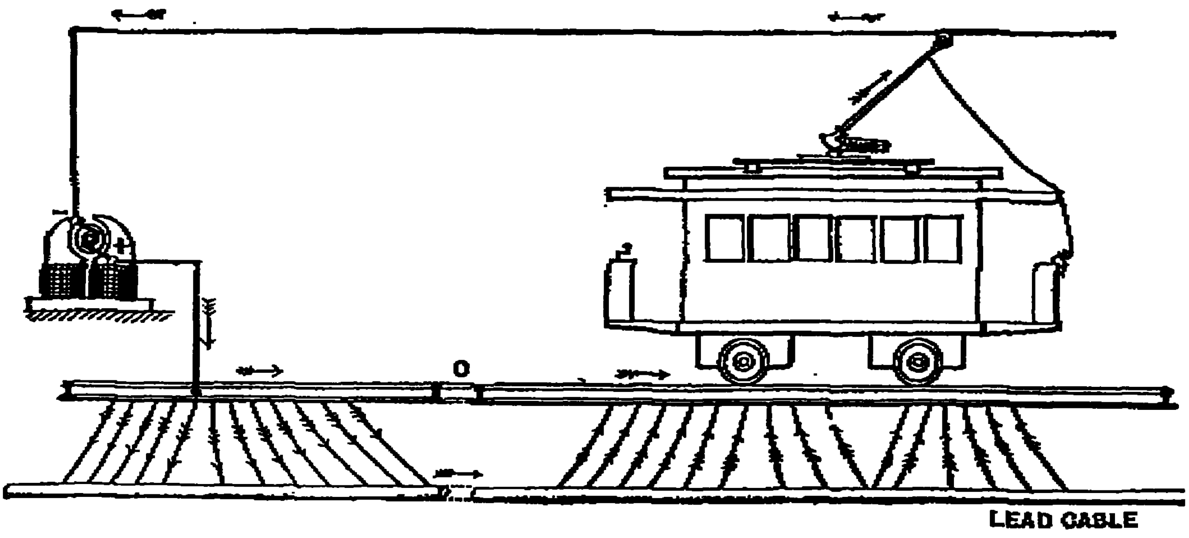


Figure 1 - Danger areas from electrolysis extended to maximum limits by the old plan of connecting positive poles of tation generator to the rails

It was formerly the practice to connect the positive pole of the station dynamo to earth, and the negative pole to trolley wire, as shown in Figure 1 with the result that the portion of the underground systems remote from the power house, covering a widespread territory, were rendered electro-positive, and the danger areas extended to the maximum limits, so the first step towards protection was taken by reversing the generator poles, rendering all the territory remote from the generators electro-negative and concentrating the electro-positive points in the immediate vicinity of the station.

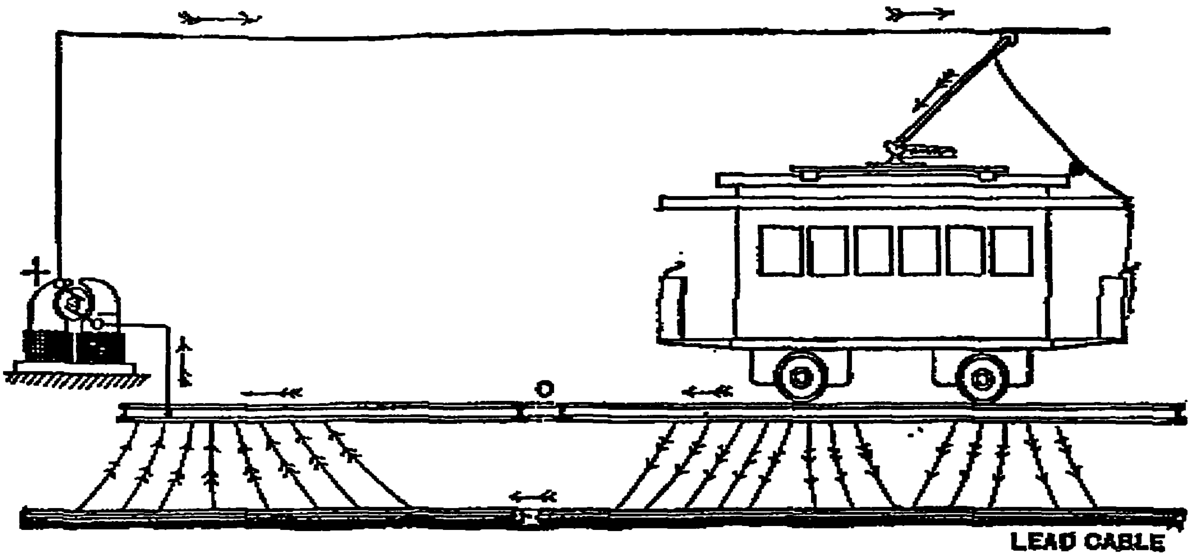


Figure 2 - Generator poles reversed in accordance with later practice bringing danger areas near the power station

By this simple expedient, illustrated in Figure 2, the first two of the three conditions have been fulfilled with the most gratifying results. Compared to a metallic conductor, the earth, even in a most favourable condition of moisture, offers a considerable resistance, and it is only with great reluctance that currents of magnitude will leave even a naked metal path for the ground. Now in the metal of the track the railways have a conductor of magnificent proportions, far exceeding in electrical conductivity any feeder system in use, requiring only adequate electrical continuity at the joints to form a path that will permit only a minute fraction of the current to leak through the earth, thus tending to fulfill the third condition.

From the specific gravity and conductivity of steel it is easy to calculate the resistance of rails in terms of the weight per linear yard, and in the diagram an attempt has been made graphically to set forth all information pertaining to the use of the rails as a return path. Curve No. 1 gives the resistance per foot of two rails in parallel, while Nos. 2 and 3 are the resistances per mile of two and four rails in parallel (single and double track). The left-hand scale is devoted to rail weight in pounds per yard, while on the lower horizontal margin are two scales. The upper one applies to Curve No. 1 and reads in micro-ohms per foot, while the lower one is for Curves 2 and 3, and reads in ohms per mile.

Thus, the resistance per foot of single track of 60-pound rail is found by selecting 60 on the left-hand scale and following a horizontal to Curve No. 1, then a vertical to the upper bottom scale, finding 4 micro-ohms. The resistance per mile of the same weight of double track is found in a similar manner, by using Curve 3, to be 0.0107 ohms.

By the diagonal lines radiating from the lower left-hand corner, and the two inner scales on the right-hand, the resistance of any number of feet or miles may be at once read. For eight miles of single track of 80-pound rail the resistance is found to be 0.125 ohms, by following a horizontal from 80 on the left-hand scale to Curve No. 2, thence a vertical to diagonal 8, thence a horizontal to the middle right-hand scale. As all scales are decimal, any range may be obtained by multiplying or dividing by ten, one hundred, etc.

Also, with the same diagonals and the second scale on the right-hand side. the fall of potential per mile maybe calculated. To ascertain the drop per mile in a double track of 90-pound rails carrying 900 amperes, follow a horizontal from go on the left-hand to Curve No. 3, thence a vertical to the diagonal 9, thence a horizontal to the second scale on the right-hand, and multiply by 100, obtaining 6.3 Volts.

From the upper left-hand corner a series of diagonals are drawn for calculating the energy expended in the track portion of the circuit, and are to be used with the outer scale on the right hand. For example:-The power lost in a mile of single track of 70-pound rails carrying 30 amperes is found by following a horizontal from 70 on the left-hand to Curve NO. 2, thence a vertical up to diagonal 30, thence a horizontal to the outer scale, giving 15 watts as the dissipated energy. As the amount of energy consumed is in proportion to the square of the current, the outer scale must be multiplied or divided by 100, 10,000, etc., when the diagonals are multiplied or divided by 10, 100, etc.

Curve No. 4 enables the weight of copper per yard of equal conducting power to any rail combination to be calculated. To obtain the amount of copper that must be supplied to be equivalent to a single track of 60-pound rails, follow a horizontal from 60 on the left-hand to Curve NO. 2, thence a vertical to Curve NO. 4, then a horizontal back to the left-hand scale, finding 21.8 pounds per yard as the required amount.

On the top of the sheet two scales will be found for use with the diagonals radiating from the lower right-hand corner. The lower one, " Weight per mile in tons," accompanies the three dotted diagonals, while the upper one, " Area in square inches," is used with the three full lines. With these scales the weight per mile or area in square inches of any rail combination, or area and weight per mile of a copper conductor having the same resistance, may be found by following a horizontal from the weight per yard on the left-hand scale to the proper diagonal and then a vertical upward to the top of the sheet and reading the desired amount on the appropriate scale.

Only a slight study of the diagram is needed to discover the value of the track as a return circuit. A double track road equipped with 80-pound rails would show a resistance of 0.008 ohms per mile. The fall of potential with a current of 500 amperes would be 3.9 volts per mile, while the energy dissipated would amount to 2006 watts, or less than one per cent. To supply a copper conductor of equal resistance, would require an area of 4.20 .square nches, weighing 58 pounds per yard, or 25.3 tons per mile, costing about USD8000, or GBP1600.

But in order to realise the full value of the rails, it is necessary to insure perfect electrical continuity, - that debatable ground upon which has been fought the battle of he bonds. While electrical discontinuity at the joints has always been recognised, its importance has always been underrated, owing to the exaggerated estimate of the value of the earth as a conductor. In early electric railway days he fish-plates merely were held to make a fair connection. Standard construction was a bit of No. 1 wire, riveted to a hole in each rail, with the addition, in gilt-edged work, of a No. 0 ground wire. Small wonder is it that electrolytic action caused the bonds to disappear so quickly as to make ailway managers declare their maintenance an mpossibility, or that the ground wires sometimes ran so hot as to actually burn the ties in two, and derail the cars by allowing the rails to spread. Could the record of the mountainous scrap heaps of burned out motors be correctly interpreted, the true epitaph of more than one defunct railway would be "Poor Bonding."

Recent experience has shown that in a street railway track properly supported by adequate paving, no allowance need be made for expansion, and, that, except for convenience in handling, the rails might be endless. A continuous track would solve some of the most difficult problems, both electrical and mechanical, that confront the tramway engineer, and as a step toward such continuity, there seems to be little reason why track building of the future may not be done with 60-foot rails, thus reducing by one half or two-thirds the present number of joints.

For those that must remain, electrical welding from the conductivity standpoint presents the best solution, but mechanically the joint thus made is open to criticism.

The cast weld joint, from a mechanical point of view, seems at present the most perfect device for supporting rail ends, but experience has demonstrated that there is not a perfect metallic contact between the rail and the casting, owing to the presence on the rail of an inevitable film of oxide, and the chill experienced by the molten metal when it first encounters the cold steel. A combination of the two methods would seem to attain the perfect joint, for the electrical weld, if properly made, would secure electric conductivity, while the casting would reinforce a system otherwise mechanically weak.

All other methods of bonding are open to the difficulty of making and maintaining two electrically perfect contacts, at each joint between two dissimilar metals. In order that such a bond should be efficacious, it is requisite that the strip forming the conducting link shall have no greater resistance than an equal rail length, and that the area of contact shall not only be equal to the cross-section of the rail, but enough greater to provide a reasonable factor of safety against possible future impairment. In these particulars rail bonds in common use have utterly failed. The usual form of bond is a piece of No. 0000 wire, upset at the ends and riveted into the rail webs. Such a wire has an area of 0.166 square inch, and is equal in conductivity to only a 10-pound rail. An 80, 90 or 100-pound rail would require 1.25, 1.41 or 1.56 square inches of copper or eight, nine or ten No. 0000 wires. Between the rail web and a No. 0000 bond wire the surface contact is about 0.7 square inch, or a little less than the area of a 10-pound rail, while 80, 90 or 100-pound rails have areas of 7.68, 8.65 or 9.61 square inches, so that, without allowing any factor of safety, the bond should have ten and one-half, twelve, or thirteen times as much contact as is at present customary, for it is perfectly obvious that, if at any point in the return circuit the resistance is increased, a portion of the current will seek the earth.

Even by restricting the danger areas to a minimum, and with the aid of a perfect rail-return to reduce the earth currents to their lowest terms, the electrical survey will show some points where corrosive action is to be expected. As disintegration takes place only where current leaves the underground structures for the earth, the last link in the protective chain is forged by attacking the electro-positive spots directly, and preventing the passage of electricity into the earth. For this purpose it has been proposed to place an additional dynamo in the station, the negative pole of which is to be connected to the pipe lines by extra wires. If the special machine be operating a few volts higher in potential than the rest of the station, its action, to use rather an unscientific hydraulic analogy, is that of pumping the electricity out of the pipe lines, and so keeping them constantly electro-negative.

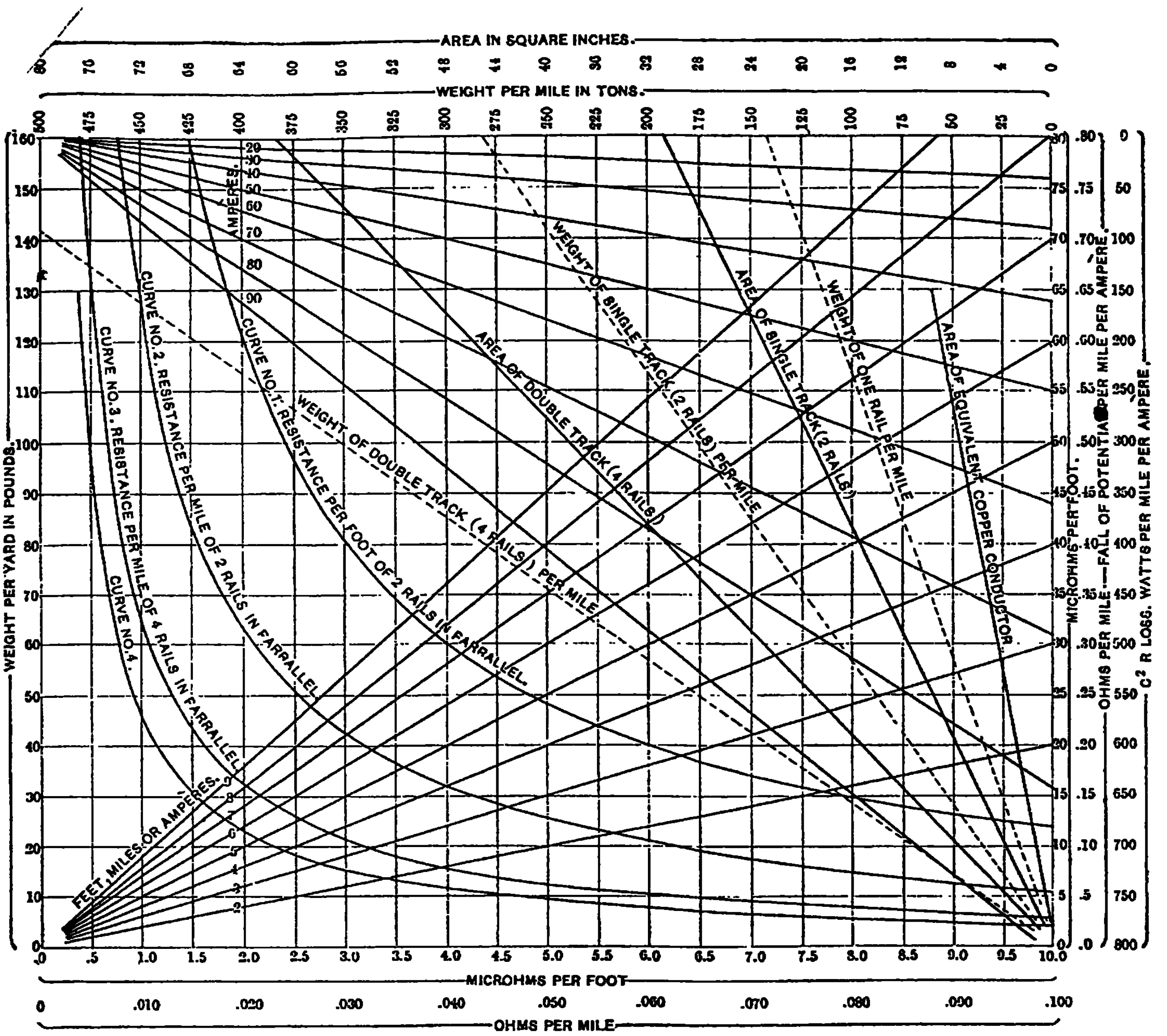
Doubtless this method is efficacious if a sufficient number of conductors are installed to reach from the special dynamo to all the electro-positive spots on the pipe lines; but if this additional set of wires be installed, the extra dynamo is superfluous, for the conductors may, at a very slight expense, be made of such low resistance compared with the soil as to completely lead away from each electro-positive site all the current that would otherwise escape into the ground.

While a protective system may thus be easily made at a slight expense and completely fulfill the object for which it was designed, it is necessary to keep a close watch over its operation by means of repeated electrolytic surveys.

If the danger to which underground metallic structures are subjected from parasitic railway currents were irremediable, or if an efficacious protecting system could be secured only by incurring an expense out of proportion to the benefits secured, there might be a valid argument for the present state of the railway return; but when the protective system is easily and economically within reach, when its adoption largely contributes to the benefit of railway companies by reducing the expense for motive power, failure to adopt it is in the nature of a deliberate infringement of the rights of others, for which there can be neither legal nor moral excuse.

Note: This article was originally published in the Electric Railway Number of Cassier's Magazine August 1899, which was reprinted in book form by the LRTA (then LRTL) in 1960.

Despite having been written 100 years ago it is still relevant today, especially with the current concern (in the UK at any rate) with leakage currents. With the abandonment, in Croydon, of the use of grassed track, despite being in common use on mainland Europe, due to concern about this encouraging leakage current it is felt that a look at the basic principles would be useful. One must wonder, that with the use of lead pipes being discouraged due to health risks and the employment of modern materials, whether our present concerns are slightly excessive.



A DIAGRAM OF RAIL RESISTANCES