BETTER GROUND GRIDS, PART II: EFFECTS OF BURIED COPPER CORROSION

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Abstract—**This technical publication explores the effects of corrosion on copper, when buried in various types of North American soils.**

Some electric power substation designers use the salt fog test for accelerated aging as a proxy for long-term evaluation of copper corrosion in a buried condition. However, although a limited useful first approximation, quantification of the corrosion effects from available empirical data shows that the salt fog test is not accurately predictive of true complicated corrosion induced by the soil, particularly sulfur compounds.

Through examination of various soil types, and using minimum 'ruggedness criteria' from IEEE Std-80, this technical publication aims to predict 1.) the loss of copper thickness over time, 2.) the associated electrical performance degradation (I^2t), and 3.) the end of useful service life. Revised corrosion rates and service life limits for grounding conductors and electrodes are presented, with emphasis on the degradation of mechanical 'ruggedness' from the effects of corrosion beyond the 10th year of buried service. Composite strip conductors, like ARMOR-965™, are shown to be designed with sufficient copper sheath thickness to remain stronger than 4/0 AWG copper cable in any soil type until the service life limit is reached.

Keywords—Corrosion, Copper, grounding contact surface area, resistance to ground, grounding conductors

I. Introduction

Much of the buried copper corrosion data was captured 50-100 years ago. Having been lost to time, it is fair to ask, "Is this data still relevant?". However, neither the corrosivity of soils toward elemental copper, nor the physical effects of corrosion, have changed. Thus, revisiting the analysis of such real-world data can be greatly valuable to substation designers today.

As a means of introduction to the subject, the efforts of the National Institute of Standards and Technology (NIST), which has long been recognized as an authority on corrosion, can be considered. Predictive formulae for the end of service life of buried copper ground grid components is not currently available from NIST, nor from its predecessor the National Bureau of Standards (NSB), because their extensive work in this field predates the modern design approach substation ground grid (c. 1953). [1, 2]

To provide simplified predictive information to modern substation designers, this technical publication organizes the available NSB data into two classes of corrosion curves: 'Standard soils' and 'aggressive soils'. Data from a marine salt fog environment is also provided for comparative context to the familiar standard assessment.

II. Rates of Corrosion

Salt fog testing of conductors per ASTM B117 (American Society for Testing and Materials) [3] and IEEE Std-81 [4] for their connections, is frequently used to measure the corrosion-resistance of various metals used for grounding. The challenge with salt fog tests is that most results are inconclusive, or at best, subjectively approved based on the visual appearance of the surface corrosion. [3, 4]

A more useful study on the effects of salt fog exists in the National Association of Corrosion Engineers (NACE) archives. In 1976, NACE published a Naval Research Lab (NRL) study conducted over 16 years in tropical environments on the effects of salt corrosion on copper [5]. Various sets of samples were exposed to different saltwater concentration, including one set of samples immersed in sea water and another set suspended in tidal wash. Tidal wash in the splash zone of sea water is the most similar condition to salt fog testing that was studied. The results show material losses due to corrosion, from which corrosion rates in various exposure environments can be approximated for making predictions for practical application. [5]

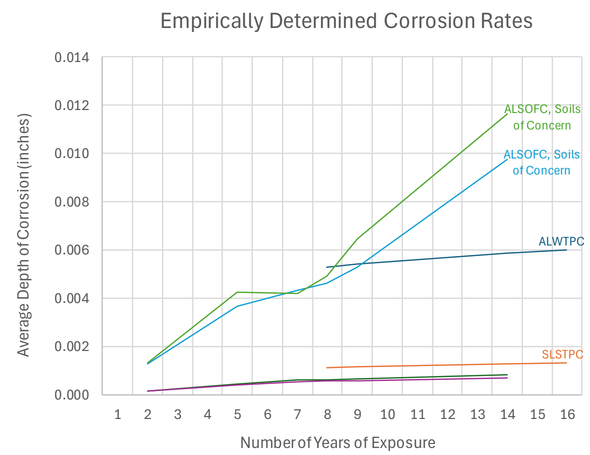
In these studies, the loss of weight in grams per square meter was measured at various time intervals corresponding to 1, 8, and 16 years of exposure. Perhaps surprisingly, corrosion of copper in salt tide measured almost identical to that in fresh water. The most aggressive loss due to corrosion was found in copper fully immersed in sea water for the duration of the study presumably due to electrolytic corrosion.

In 1957, the National Bureau of Standards published a similar, but much more comprehensive, study of soil related corrosion. The study was conducted over 14 years in 47 buried environments across the United States. The study was performed on 333 various grounding materials, including the effects on buried copper. Different sets of copper pipe samples were exposed to a range of soils from 1932 to 1946 and measured at time intervals corresponding to 2, 5.4, 7.4, 9.3, and 14.3 years of exposure. As in the NRL study in water environments, losses quantified by the NSB in soil environments were initially measured in mass per year and were then converted to depth of corrosion in inches per year. [1]

For this technical publication, the 67-year-old data from the NSB study was then reduced by the authors into two broad groups: 'Standard soils' and 'aggressive soils'. This categorization permits convenient comparison with the 48-year-old data from the NRL study for tropical environments exposed to humid air conditions.

One soil type in the NSB study was omitted completely, that of cinders, so as not to detract from the trend for the other aggressive soils. Rates of corrosion of all copper alloys are very high in cinders (wood ash, etc.) due to the high sulfur content, which should be avoided as a backfill material by substation designers. The remining soil types are more challenging to distinguish from each other in the field.

Fig. 1 shows the resulting corrosion rates for this study for copper in both tropical and soil environments.



# of Years Exposed	FROM NRL DATA (1976) AL_{WTPC} Sea Water Aggressive TP Copper	SL_{WTPC} Tidal Wash Standard TP Copper	FROM NIST/NBS DATA (1957) SL_{SOFC} Soils A Standard OF Copper	AL_{SOFC}, Soils of Concern Aggressive OF Copper	SL_{STPC} Soils A Standard TP Copper	AL_{STPC}, Soils of Concern Aggressive TP Copper
1.0	0.00120	0.00070				
2.0			0.00015	0.00129	0.00017	0.00131
5.4			0.00044	0.00365	0.00039	0.00423
7.4			0.00062	0.00432	0.00054	0.00419
8.0	0.00530	0.00110	0.00062	0.00462	0.00055	0.00490
9.3	0.00541	0.00113	0.00064	0.00529	0.00057	0.00645
14.3	0.00585	0.00126	0.00081	0.00977	0.00070	0.01164
16.0	0.00600	0.00130				

Fig. 1. Corrosion rates for copper derived from available data sources

We have labeled the lines on the chart by the following convention, used throughout this technical publication:

- SL_{WTPC} = Standard Losses in Water for common Tough Pitch Copper (TPC)
- AL_{WTPC} = Aggressive Losses in Water for common Tough Pitch Copper (TPC)
- SL_{STPC} = Standard Losses in Soil for common Tough Pitch Copper (TPC)
- AL_{STPC} = Aggressive Losses in Soil for common Tough Pitch Copper (TPC)
- SL_{SOFC} = Standard Losses in Soil for common Oxygen Free Copper (OFC)
- AL_{SOFC} = Aggressive Losses in Soil for common Oxygen Free Copper (OFC)

Several notable observations can be made from the corrosion rates presented in Fig. 1.

First, the corrosion rates for tough pitch copper in tidal wash (SL_{WTPC}) are a match with those of buried oxygen-free copper (SL_{SOFC}) in standard soils as indicated by the close overlap. Additionally, the corrosion rates for buried tough pitch copper (SL_{STPC}) in standard soils are only marginally higher than that of tidal wash (SL_{WTPC}) or buried oxygen free copper (SL_{SOFC}).

Second, the study of copper that is continually immersed in salt water (AL_{WTPC}) shows rapid loss rates for the first ten years. However, corrosion then tapers off to the same rate as the tidal wash group, causing little concern for extended service life.

Significantly, four out of six environments examined are relatively benign regarding the effects of copper corrosion in buried environments which underlines the suitability of copper in underground applications.

Third, however, the corrosion rates of common tough pitch (AL_{STPC}) or oxygen free (AL_{SOFC}) copper in some soils, labeled as "soils of concern", tend to lose about 0.001 inch (also known as "one mil") of copper on average per year, starting at around the 10th year.

This is an alarming rate, especially in consideration of the useful service life of electrodes extending deep into the earth. These are almost always "10-mil ground rods" made of copper clad steel with 0.010 inch (10-mil) of copper. These soils will require corrosion mitigation techniques for extended service life.

Table 1 presents revised equations for corrosion in buried soils, based on the empirical data presented in Fig. 1.

Note that items #3 and #4 are the equations for *"soils of concern"*. In such soils, common 10-mil ground rods are predicted to survive less than 15 years before being completely consumed into the soil by corrosion. This corrosion rate would be accelerated by any stray currents flowing into the system, which were not considered in the study.

TABLE 1. PREDICTIVE EQUATIONS FOR THE EMPIRICAL LOSSES FOR BURIED COPPER SURFACES DUE TO CORROSION BY THE SOIL.

	Environment	Predicted Loss (inch)
1	SL_{STPC}	= 0.00060 + (0.000026) * (No. of Years - 10)
2	SL_{SOFC}	= 0.00068 + (0.000034) * (No. of Years - 10)
3	AL_{STPC} *Soils of concern*	= 0.00756 + (0.001040) * (No. of Years - 10)
4	AL_{SOFC} *Soils of concern*	= 0.00625 + (0.000900) * (No. of Years - 10)

Soils of concern, as identified herein for the first time, include at least the following:

Known Soils of Concern

- "Muck" in New Orleans, Louisianna.
- "Chino Silt" in Wilmington, California.
- "Docas Clay" in Cholame, California.
- "Rifle Peat" in Plymouth, Ohio.
- "Tidal Marsh" in Charleston, South Carolina

III. END OF USEFUL SERVICE LIFE

Using the corrosion equations in Table 1, it is now possible to identify the dimensions of copper thickness required to achieve any stated service life duration.

IEEE Std-80, the "IEEE Guide for Safety in AC Substation Grounding", has never specified an acceptable rate of corrosion for the metals presented, including copper, nor any criterion for determining the end of useful service life. [6] Some engineers define a minimum acceptable service life as 30 years, which is a typical practicing career. CIGRE specifies the normal life of switchgear as 25 years, and this lends credence to a 30-year lifecycle. At the conservative extreme, some service define it as 50 years, which is a more ideal service life intended to match the service life of an oil-filled substation transformer (CIGRE specifies 45 years).

The challenge is how can a substation design engineer predict the actual end of life of a conductor during selection? Annex B, "Sample Calculations", based on [6] provides a rationale which can be adapted for this purpose. Annex B shows the calculation for the minimum conductor size of an application that results in No. 4 AWG copper. Then, it upgrades the result to become 2/0, citing *"mechanical strength and ruggedness requirements"*. Thus, it seems reasonable to assume that 2/0 copper defines the minimum acceptable break load strength of a buried conductor throughout its service life. Perhaps, this minimum could be reduced to 1/0 AWG or #2 AWG. However, we have selected soft drawn 2/0 AWG break load force of 3,105 lbs (i.e.. = 90% * area * 33,000 psi). This corresponds to an electro-thermal (I^2t) withstand capability of 360 amp^2-seconds—as the reasonable end of service life capacity for a standard soft drawn 4/0 AWG copper ground grid. For context, selecting 1/0 AWG as the end of service life would only extend service by another 5 years. [6, 7, 8, & 9]

A different rationale is needed in the theft-prone areas where copper-clad steel (CCS) stranded conductor has been adopted. ASTM B910, "Standard Specification for Annealed Copper-Clad Steel Wire", specifies the thickness of copper and the strength of the diffusion bond between copper and steel. The copper thickness is 9%-10% of the radius of each wire upon installation, per the B910 standard for 40% IACS CCS. For 19#9 CCS comprised of No. 9 AWG wire strands, with diameter of 0.114 inch, the average copper thickness is 0.010 inch, or 10-mil like a common CCS ground rod. [10]

Without a copper sheath, the exposed steel alone corrodes rapidly and will be consumed within about 10 years when buried in standard soils. For 10-mil CCS, then, it seems reasonable to define the end of useful service life of a buried conductor or ground rod is when the average penetration or pitting of corrosion first reaches the steel core. That is, the corrosion-resistance depth of the sheath is 10-mil less 6-mil for pitting, equals only 4-mil remaining. [1]

For new composite flat grounding conductors, like Armor-965, the copper sheath is 0.024 inch (24-mil) thick, similarly, corrosion down to the core defines the end of service life. But this occurs much later because the service life is not proportional to the Cu thickness. That is, the corrosion-resistance depth of the sheath is 24-mil less 6-mil for pitting, equals 18-mil remaining. A comparison of the starting sheath thickness in cross section is shown in Fig. 2.

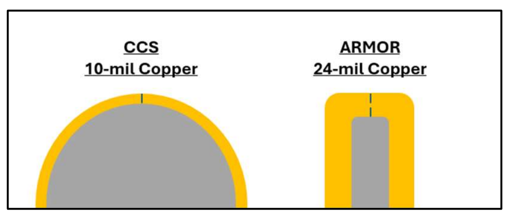


Fig. 2. Comparison of sheaths for CCS and Armor with dashes representing approximately 10-mil thickness.

The resulting comparison of expected service lives for commonly used and newly developed grounding conductors and electrodes is shown in Table 2, with supporting details and calculations presented in the graphs and associated tables shown in Figs. 3 & 4.

The column on the right side of Table 2 labeled "Max. Years Std Soil" refers to standard soils (SL_{STPC} & SL_{SOFC}). Similarly, the column labeled "Max. Years Agg Soil" refers to aggressive soils (AL_{STPC} & AL_{SOFC}).

Stray currents in the soil may account for around 10-year faster corrosion rate and reduced service life for the conductors presented in Table 2. This rate would vary widely and is only stated for comparison. On the other hand, corrosion mediation techniques, like tinning, may (partially) negate this by extending service life by about 10 years. It may be possible to use additional coating solutions between the copper and soil to extend service life even longer. [5, 11]

TABLE 2. END OF USEFUL SERVICE LIFE FOR COMMONLY USED GROUNDING CONDUCTORS AND ELECTRODES

	Type	Metal	Limit	Max. Years in Std Soil	Max. Years in Agg Soil
A	Armor-965	Cu-Fe	24-mil Sheath	150+	35
B	4/0 AWG	Cu	2/0 Equiv.	150	30
C	Ground Rod	CCS	10-mil Sheath	75	15
D	19#9	CCS	10-mil Sheath	75	15

IV. DIMINISHING STRENGTH

Copper losses due to corrosion are mostly uniform across the surface, except for localized pitting. [1] Standard 4/0 copper ground grids exhibit radial losses on each strand. Thus, loss of mass at rates presented in Table 1 can be converted to loss of strength as a function of a reduced cross-sectional area.

An analysis of strength as a function of buried service life is presented in Figs. 3 and 4. A downloadable engineering drawing XDWG-104 is available at ExeterGround.com under the "Technical Publications" section for further detailed examination. [12, 13]

CCS ground rods and 19#9 conductors have core steel surrounded by a 10-mil copper sheath. When corrosion penetrates to the core, corrosion of the steel accelerates quickly driven by the high electrochemical (galvanic) potential between copper and steel.

Contrasting with standard ASTM CCS performance, ARMOR-965™ has a core metal surrounded by a 24-mil copper sheath. After being buried for 140 years in standard soil, the ARMOR sheath is reduced from 0.024 inches (24-mil) at installation to 0.014 inches (14 mil). The 14-mil remaining sheath is 40% more than a freshly installed 10-mil CCS ground rod. Moreover, in aggressive soils, ARMOR remains significantly more rugged than soft copper because its copper sheath layer protects the core and strength is little affected until the steel is exposed and starts to corrode.

V. CONCLUSIONS

Empirical results indicate a knee in the corrosion rate curve for copper between the 5th and 10th year of exposure. This is true of the influence of corrosion, largely independent of the exposure environment. Salt fog testing is shown to be of limited value. Instead, empirical data from past studies is shown to provide a solid basis for predictive corrosion rates in buried soils, which are more severe than corrosion in marine environments. Some soils will consume a 10-mil copper sheath in 15 years of service life. However, in the same aggressive soils, new composite flat grounding conductors, like ARMOR-965™, are sufficiently rugged to extend the usable service to 35 years, while remaining more mechanically rugged than 4/0 copper over its maximum comparative service life of 30 years, at which point 4/0 copper performs like 2/0 copper. In another CEATI paper [14], the improvement in reduction of electrode resistance with equivalent flat Shining Armor conductors over standard stranded variants as used presently has been demonstrated. This advantage coupled with the superior service life to cost of ARMOR conductors renders them an optimal choice for the substation of the future and as an upgrade for existing stations.

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VITAE

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