Objective: Present a summary view of certain design elements within the overall ground bed design process, in order to emphasize the significance of current discharge density as it affects groundbed drying. Although, for the most part deep wells designed for cathodic protection work well, occasionally systems fail due to increasing resistance. This article stresses Soil Drying consideration into the design of deep wells in order to improve deep well design success. Appendix A is a Deep Well Design Flow Chart that places *Current Density to Soil* in perspective in the design sequence. The focus of this article is to overcome electro-osmotic drying in groundbeds, using a deep well application example.

Background: Anodes must be placed in soils or electrolytes to function in cathodic protection. HSCI anodes work well in natural waters, but in the ground they are rarely buried directly without being bedded in high quality carbonaceous backfill (coke). In the early years of CP in North America various types of anodes, buried directly in soil without coke, went "high resistance" very quickly because the burial zone dried out. In other instances, gases produced by the CP discharge blocked current transfer. The use of coke with vent pipe became widely accepted to increase the area of anodic surface in contact with the earth and prevent gas blocking. This mitigated soil-drying and reduced groundbed resistance. Coke breeze also prevents internal collapse of otherwise open deep wells.

Groundbed Design Considerations: Example 1. This example is based upon a deep well, focusing on the configuration of the anodes and backfill column. For more extensive treatment refer to (1) Lewis, T.H., Deep Anode Systems, Design, Installation and Operation, Loresco 1997 and (2) Peabody's Control of Pipeline Corrosion, NACE 2nd Edition 2001. Design of shallow groundbeds is not dissimilar; with some straightforward adaptations. Also see: "Performance of Deep Groundbeds in Western Canada" by W.B.Holtsbaum.

Assume 40 Amps requirement, determined from CP engineering and experience (not covered here).

Assume 20 year Life (800 Amp-yrs.). It should be kept in mind that, with the passage of time, many structures end up (a) functioning for many more years than originally intended, and (b) expanding, which usually increases demand for CP current. Of the total expenditure for a CP system, the percentage related to the consumables (anodes and coke) is likely to be a relatively small portion of the whole. Therefore the cost to add more mass of anodes and coke in order to extend CP life (or coverage if the rectifier and cable are not operating close to capacity) will be very modest. With this in mind, the coke and anode materials necessary to handle the 800 Amp-years requirement can be estimated, as follows:

Total HSCI Anode Mass Requirement: Net HSCI Anode weight required = Amp-years / Consumption Rate lb/A-yr = 800 A-yr x 0.75lb/A-yr = 600 lb net. Gross HSCI Anode weight required, to account for the proportion of the anode weights that cannot be practically consumed, but nevertheless must be used = Net weight / Utilization = 600lb / 85% (for tubular anodes) = 706lb gross. Consumption Utilization

Consumable Backfill Requirement: 800 Amp-yrs / 2.2lb per Amp Year = 364 lb (at say 70lb/cuft = 5.2 cuft.). This is an idealized amount assuming that all current is transferred from the anode through the coke into the soil, and that coke is consumed at 2.2 lb/A-yr. In practice, a portion of the current from an anode will pass through electrolyte, and some conditions are less severe than others. Jakobs (3) reports that the average consumption of graphite is of the order of 200g/A-yr (0.45lb/A-yr), but (in the presence of oxygen and sulphates) it may exceed 1kg/A-yr. As coke backfill is consumed, ash builds up sending more current through the electrolyte. Therefore, the assumption that every ampere discharged from the anode will consume coke at 2.2 lb/A-yr is quite conservative, especially in the relative absence of oxygen and sulphates.

The Total Amount of coke loaded into a deep well can be viewed as 2 elements:

(1) Active Coke surrounding the anodes, to be consumed by transfer of current from anodes to soil.

(2) Bank Coke, situated above the active zone to replenish active coke as it is consumed.

The Coke Bank located above the uppermost anode is assurance that, in the end, every anode will remain covered with coke. Experience has demonstrated that Deep Wells tend to go high-resistance at the top if insufficient coke is banked above (T. Wilken private communication). As a factor of safety, somewhat more than the calculated ideal amount is prudent. Lewis [1, p51], suggests a Utilization Factor of 25%, equivalent to a Factor of Safety of 4 times. Others advocate bank allocations closer to the ideal amount. For example: One rule-of-thumb is "20 feet of coke above the last-anode-in". For purposes of this example, Table 1 lists Coke Bank Lengths calculated for various well diameters using a Factor of Safety of 1.5x, based on 364lb x 1.5 = 550lb, at 70lb/cuft = 7.86 cuft, rounded off to 8 cuft coke volume.

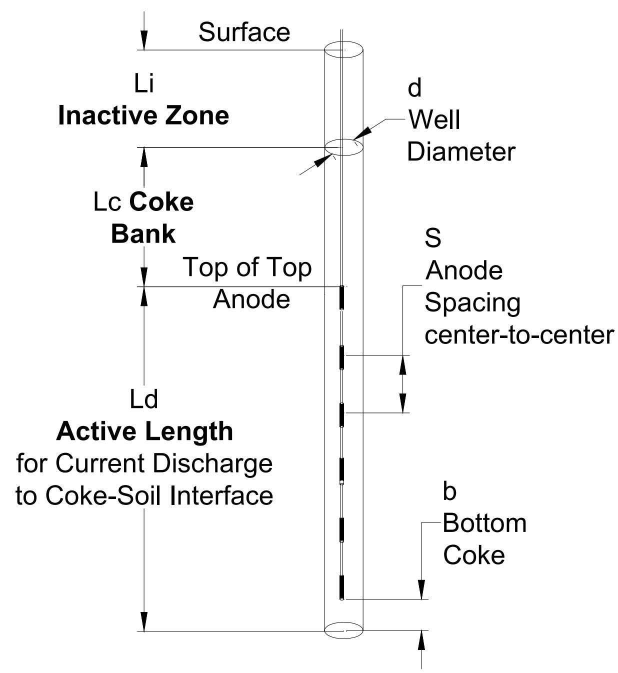

FIGURE 1 Deep Well Elements

Table 1: Length of *Consumable Coke Bank* according to well diameter, for 800A-yrs, Example 1.

Well Diameter	inch	8	9	10	12
Cross Section	sq ft	0.35	0.44	0.55	0.79
8 cuft Coke Length	ft	23	18	15	10

Note: The compacted density of coke varies according to the source. For examples: www.Loresco.com or www.Asbury.com

The Total Length of the deep well can be visualized as three distinct zones, starting from the surface, as shown in Figure 1 on the prior page**:**

A) an <u>Inactive Zone</u> between the surface and the top of the coke column.
Presence of a relatively high resistance layer within the Inactive Zone helps distribute the CP current effectively along the structures to be protected.

B) the pre-determined <u>Coke Bank Length</u>, and

C) the <u>Active Zone</u> containing anodes bedded in coke. (to be determined)

Occasionally deep wells have exceeded 700 ft total length (depth). This section addresses calculation of Active Zone Length.

Active Length may be defined as the distance from the top of the upper-most anode to the bottom of the drilling. This length may be increased or decreased as the design develops, within the limits of acceptable geology. In a perfect world, anodes bedded in coke will be consumed to their utilizable limit precisely when the "ideal" volume of coke bank is used-up. A perfect groundbed (with no extra "safety factor" coke in the bank) will continue to pass current efficiently until the top crown of the coke bank reaches the upper-most anode (in its heavily consumed state). At this time, the current discharged from the coke to the soil should not be appreciably more than the current density limit for the soil. With extra coke banked for safety, current density will be proportionally less than the limit.

It is normal that geological strata intersected by a deep well exhibit varying characteristics, including resistivity and electro-osmotic sensitivity. If, at any point in the life of the well, current discharge density materially exceeds the drying limit for certain strata, localized drying may drive up the resistance at those sites. Current will naturally redistribute to lower resistance zones, which in turn may also dry out. Eventually, rising voltage requirements may limit-out the rectifier's ability to maintain current. These chain-events may be of no consequence, or may become catastrophic, depending upon characteristics that may not be easily predictable before the fact. Clearly, inspection of drill samples combined with down-hole measurement of strata resistances (before the well is filled), can be used to improve performance and avoid failures Refer to Performance of Deep Groundbeds in Western Canada and Earth Materials: Resistivity & Electro-Osmotic Potential [in development #32].

For purposes of Example 1 assume 0.125 A/sq ft (1.35 A/sqM) as a practical Current Density Limit for the Active Length.

Table 2: Combined Active Coke and Coke Bank Lengths for typical Drill Diameters**,** for Example 1.

Well Diameters	d	inch	8	9	10	12
Surface Area sq ft per 100 ft length	As	sq ft	209	235	262	314
Current Limit 0.125 A/sq ft	I soil	A/sq ft	26.1	29.4	32.8	39.3
Active discharge Length for 40A	Ld	ft	153	136	122	102
Active Length + Coke Bank =	Ld + Lb	ft	176	154	137	112

Note: Drilling Depth = Active (discharge) Length Ld + Bank Length Lb + Inactive Length Li (Ground Surface to Coke Bank).

To the extent that the Coke Bank includes a substantial factor of safety, enough coke will be left in the bank to augment the active length of the well. For the 9" well in this example; with coke consumption of 2.2 lb/a-yr and a factor of safety of 1.5, the life-end length of coke will be (136ft + 17.3ft) = 153 ft, which is 12.7 percent more than is required to meet the 0.125A/sqft limit.

Selecting and Distributing Individual Anodes within the Active Length of the Deep Well Column

From page 1: Net HSCI Anode weight required = Amp-years / Consumption Rate lb/A-yr = 800 A-yr. 800 A-yr at 0.75lb/A-yr = 600 lb net.

Gross lbs = Net lb / % Utilization = 600 lb net / 85% Utilization = 706 lb gross.

A nominal 0.75lb/A-yr consumption seems appropriate for anodes operating at up to 1 a/sqft in coke breeze, with vent pipes. At significantly higher current density (anode to coke), consumption will increase to an extent depending upon the environment. Presence of SO4 ions and lack of soil permeability will also increase consumption. Refer to: Anode Life, Utilization and Consumption .

Given the gross weight of anodes to be distributed within the active length of the column (which is a function of the geology and current density limitations), unit weights of anode options can be used to calculate *weight-distribution based* anode spacing as shown in Table 3. Warning: *weight-distribution based* anode spacing might not be compatible with electro-osmotic current density limitations.

Table 3: Tubular Anode Options and spacing for 9" well dia for Example 1.

Typical Anotec tubular anodes by Type:	**2284Z**	**2660Z**	**2684Z**	**3884Z**	**4884LZ**
anode Length, ft (La)	7	5	7	7	7
Weight each, lbs	50	50	70	90	123
Ni= ~ Number (fractional) required for 706lb total gross weight	14.1	14.1	10.18	7.8	5.7
N = Integer of Ni (practical whole number required)	15	15	11	8	6
Spacing, ft center-to-center, from the formula: S=(Ld-La-b)/(N-1) where: S = c/c spacing, Ld = active discharge length, La= anode length and b = length of coke below bottom anode (5' assumed).	8.9	9.0	12.9	18.4	25.8

At first glance it may seem that the heavier anode options appear attractive due to:

- Less cable (unless all anodes are on one string of cable, putting all the eggs in one basket) Refer to Electrical Cable for Cathodic Protection for chlorine resistant insulation for cables in deep wells.
- Slightly reduced associated costs of construction.

However, heavier anodes widely spaced, increase the risk of soil drying. This is because increased spacing increases variability between the peaks and the valleys of current density along the coke column. This phenomenon is termed A*ttenuation* (meaning diminishment) because current passing down the coke column diminishes as a proportion passes out of the coke into the soil. Lewis (1, p 105) calculates that current density to soil at anode locations is greater than anywhere between anodes. Moreover, the fewer the number of anodes, and the greater the spacing between anodes, the greater the difference will be between peak levels and the average level of current density. Therefore sensitivity to osmotic drying (and gas generation) is accentuated at the anodes.

Lewis [1, p 107] controls spacing to limit "maximum current density variation (to) 25% along the column." In an example calculation he establishes maximum spacing for 2 anodes in homogeneous soil, over a representative range of well diameters and resistivities for soil and coke. In his example [1, p 109] maximum spacing equates to 43 ft for a 9" well in 5000 ohm-cm soil with 3 ohm-cm coke breeze. For the same well in 2000 ohm soil, the spacing limit decreases to 27 ft. Lewis's *Attenuation* model is a simplification of reality, but the principal holds. Close spacing is preferred when electro-osmotic drying is a possibility and soil resistivity is low. This is applicable irrespective of the anode material used. It should be kept in mind that Lewis's example is based on several significant simplifications. Nevertheless, the need to limit spacing in soils sensitive to drying is clearly established.

What is interesting however, is that Table 4 indicates that only at soil resistivities below about 2000 ohm-cm will Lewis's Spacing Limits affect the anode-spacing derived for Example 1 in Table 3. Keep in mind that Lewis's figures are not absolutes; only examples.

Table 4: Anodes spacing limits derived for Example 1 in Table 3, compared to Lewis's spacing limits defined by application of his *Attenuation* model.

From Table 3 for Example 1	Tubular Anodes	Type	2284Z	2660Z	2684	3884Z	4884LZ
	Quantity Required for 800 Amp-Yr Service	Qty	15	15	11	8	6
	Center to Center Spacing to fit 136ft Discharge Length	ft	8.9	9.0	12.9	18.4	25.8

Lewis's Spacing Limits by Attenuation model p 109: 9" well, 3 ohm-cm coke	Soil	Limit
	5000 ohm-cm Soil	43 ft
	2000 ohm-cm Soil	27 ft
	1000 ohm-cm Soil	19 ft

Spacing of anodes may also be viewed from another perspective. Holtsbaum[4] makes the case for preferentially locating anodes in zones of low resistivity, equivalent to squeezing more of the anodes into lower resistance strata. If this is accomplished without drying the soil, total system resistance will be reduced, and anode consumption will be more uniform.

Implications relating to Anode Sizing and Spacing for Example 1 according to Table 4**.**

- Eight 3884 Z of 816 A-yr, spaced at 18.4ft, fulfill the requirement for 800 A-yrs at less than 19ft spacing in 1000 ohm-cm soil.
- Six 4884LZ of 836 A-Yr should be spaced at 25.9ft to fit the 136ft active length required (5ft coke-bottom, 0 ft coke-top). But this well violates the 19ft Attenuation Control Limit. Furthermore, if the six anodes are installed at 19ft centers in the center of the active zone, current density there is increased beyond the Soil Current Density Limit.
- Consider seven 4884LZ anodes, spaced at (Ld-La-B)/(N-1) = (136-7-5)/(7-1) = 20.7ft, slightly beyond the 19ft limit
- Note that Lewis's19ft limit was derived from very simplified assumptions. For example: Lewis's "point anodes" concentrate discharge, whereas 7 ft tubulars spaced at just under 21ft significantly spread current discharge, reducing the critical peak levels.
- Furthermore, mathematical modeling (supported by forensic inspection of recovered anodes) has clearly shown that current discharge density off anodes is much higher at the anode ends than mid-

length. Iossel (5), by mathematical modeling, suggested that a 5 to 1 end-effect ratio applies to 5 to 7 foot anodes. This phenomenon decreases current-density variation in coke between anodes.

- It follows that a 20ft spacing for seven 4884LZ anodes is probably acceptable for 1000 ohm-cm soil.

For an economic analysis of the implications of these considerations, refer to Deep Well Costing for Example 1 (pending #37) (in development).

Anotec High Silicon Cast Iron Tubular Anodes are available in a range of weights to suit deep wells. New Z-Series tubulars have reduced diameters relative to traditional high silicon tubular anodes, freeing up more space (# 38) for cables, vents, stand pipes, coke and installation freeboard. These features give the designer more choices for enhancing the value of their CP systems.

References:

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1. Lewis, T.H., Deep Anode Systems, Design, Installation and Operation, Loresco 1997
2. Peabody's Control of Pipeline Corrosion, NACE 2nd Edition 2001
3. Jakobs J.A., "A Comparison of Anodes for Impressed Current Systems" NACE Regional Presentation 1980 (L45)
4. Holtsbaum, W.B., "Performance of Deep Groundbeds in Western Canada" NACE Regional Presentation 2001 (L47)
5. Iossel Y, (Pending)

References Note: Superscripts reference Anotec Document Numbers
- (22) = reference listed below
- (#22) = Anotec Article
- (L22) = Anotec Private Library Item

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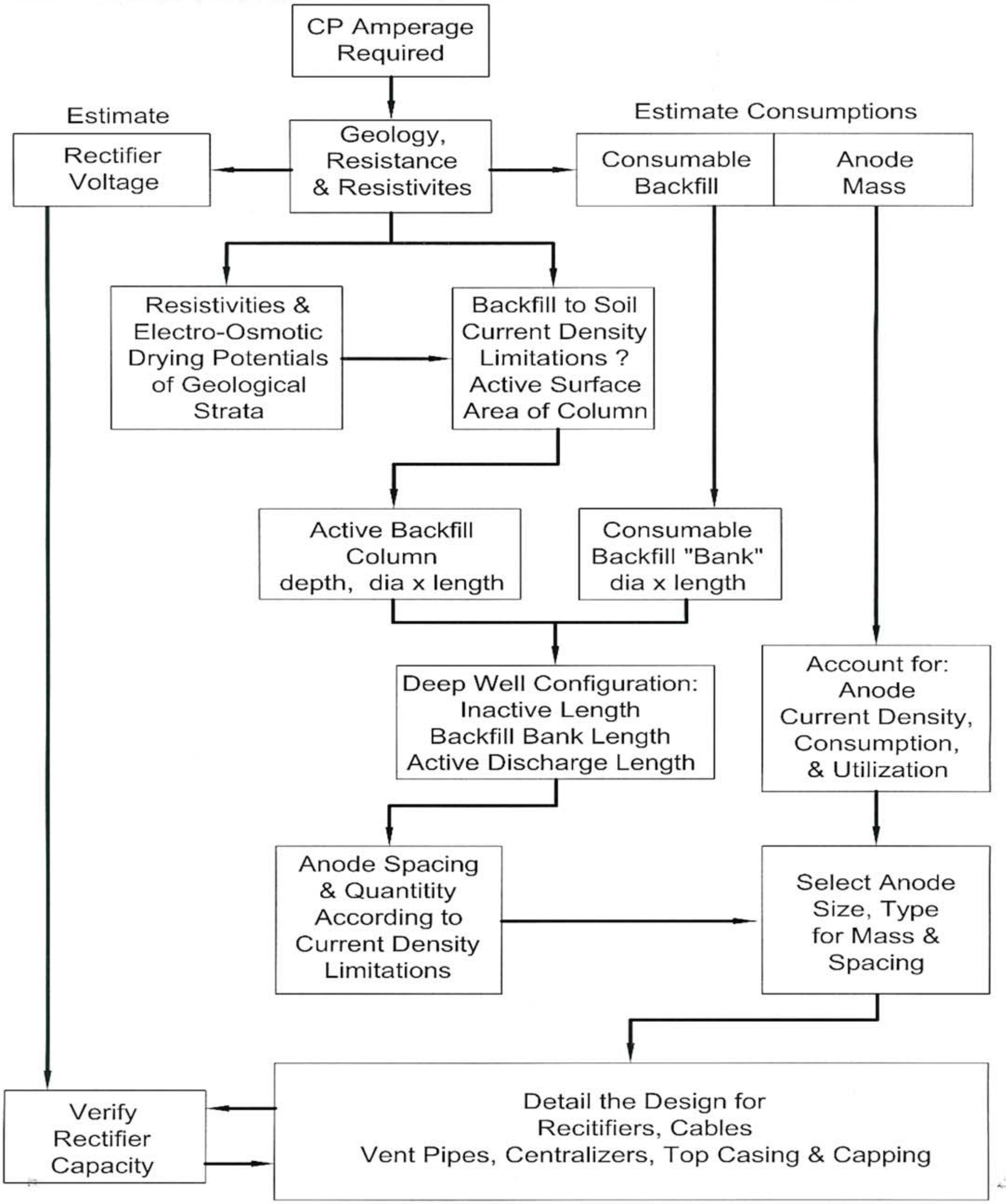
CP Amperage Required
Estimate
Rectifier Voltage
Geology, Resistance & Resistivites
Estimate Consumptions
Consumable Backfill
Anode Mass
Resistivities & Electro-Osmotic Drying Potentials of Geological Strata
Backfill to Soil Current Density Limitations ? Active Surface Area of Column
Active Backfill Column depth, dia x length
Consumable Backfill "Bank" dia x length
Deep Well Configuration: Inactive Length Backfill Bank Length Active Discharge Length
Account for: Anode Current Density, Consumption, & Utilization
Anode Spacing & Quantitity According to Current Density Limitations
Select Anode Size, Type for Mass & Spacing
Verify Rectifier Capacity
Detail the Design for Recitifiers, Cables Vent Pipes, Centralizers, Top Casing & Capping