Underground Distribution Reliability: The 5•Ps

Glen J. Bertini
Novinium, Inc.

***Abstract*: Reconciling the financial considerations of the underground distribution circuit owner with the reliability needs of its customers has traditionally been viewed as a zero-sum-game with the circuit owner on one side and the electrical customer and the regulator on the other. This paper introduces a hierarchy of needs which allows an appropriate balance to be optimized and sustained … maximum reliability with the highest capital efficiency. Various strategic and tactical options may be viewed through the prism of the hierarchy of the 5•Ps (i.e. 5 cable populations: post-failure, problematic, preemptive, proactive, and preventative). A simple net present value (NPV) analysis is overlaid on the 5•Ps and quickly leads the circuit owner to the optimum strategic and tactical choices. Data from field experience provides validation of the models employed and benchmarks for the circuit owner to compare their own strategies and tactics.**

INTRODUCTION

The legacy of over two billion feet of pre-1980 vintage underground cable [1] provides electric distribution utilities and their regulators with a considerable challenge over the next two decades. The failure rate for this population of cables is in excess of 10 failures per 100 miles per year at the one North American circuit owner where over a decade of failure history has been compiled. There is nothing extraordinary about the cable design, installation practices or operating practices of this circuit owner, except that its cables are buried in hypothermic soil. Some circuit owners may take solace in the reductions to reliable cable life suffered by cables in hyperthermic soil temperature (found in Texas, Arizona, and Florida in North America) [2, 3] and high lightening strike density. In the end, cooler temperatures and fewer lightning strikes only delay the inevitable.

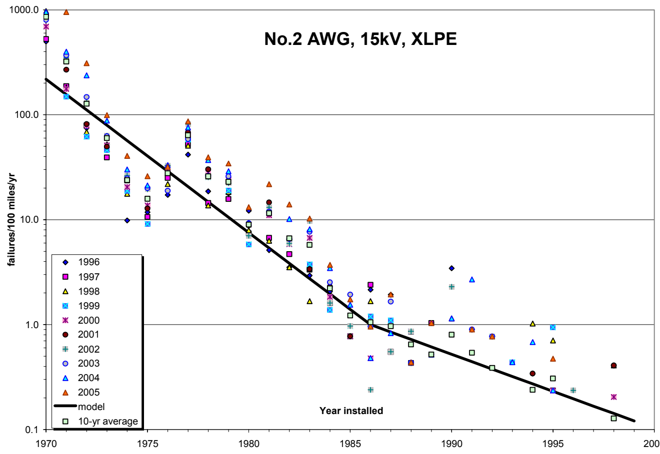

Figure 1. The failure rate of pre-1985 vintage cable at this North American utility is unacceptably high.

Rehabilitation cost can vary from a typical replacement cost of $24.25 per cable foot to typical rejuvenation (silicone injection) cost of $7-8.00 per cable foot. These typical costs provide upper and lower bounds for North American rehabilitation of $48 billion and $14 billion respectively for the two billion feet of these cables still in service. The rising cost of aluminum and copper are likely to push the cost of replacement upward faster than the general rate of inflation, making the replacement option increasingly painful.

The distribution utility is caught between two inexorable forces. The first is the Second Law of Thermodynamics, which provides cold assurance that cables not rehabilitated will be less reliable tomorrow than they are today. Perhaps the only force more immutable than the Second Law is the ever increasing reliability expectations of the electrical consumer in the developed world. These evolving expectations include ever more reliability at little or no extra cost. Businesses and residential electrical users become more "digital" every day and hence are ever more dependent upon a reliable supply of power.

Rising generation costs place continuous upward pressure on electrical rates. Regulators are reluctant to allow rate increases in general, and for distribution reliability in particular, as exemplified on the front page of the Wall Street Journal [5].

> Southern California Edison, … recently sought approval to replace 800 miles of aging underground cable, … after concluding cable failures were the leading cause of controllable outages. But consumer advocates at the California Public Utilities Commission fought the $145 million request, arguing that there was no proof that the worst cables would be replaced first, given inadequate utility records.
>
> Instead, the utility got permission to replace only 300 miles of cable at a cost of $54 million. An administrative law judge acknowledged the reduction might mean "running cable to failure" and "poorer system reliability than what customers experience today."

Driven by political considerations, regulators are more likely to allow cost recovery for conservation programs or the development of renewable sources of power. On the other hand, the same regulators appear ever more eager to impose performance-based rate-making penalties on distribution utilities that are not able to maintain a threshold level of reliability.

Within the constraints of these realities, the operators and engineers of distribution networks must aggressively implement cost saving strategies and prioritize their spending to optimize their return on capital.

HIERARCY OF NEEDS

Every undergraduate college psychology course introduces Maslow's hierarchy of needs, depicted in Figure 2. The essence of Maslow's famous work can be boiled down to the common sense considerations each of us would make if we were stranded on the proverbial desert island. We would first look for water, food and shelter at the base of the pyramid. Only after we satisfied the needs at the lowest level of the pyramid would we begin to expend significant resources on the next level up. Only after the foundational levels of the pyramid are completely satisfied do we spend resources near the top of the pyramid on such notions as self esteem and self actualization.

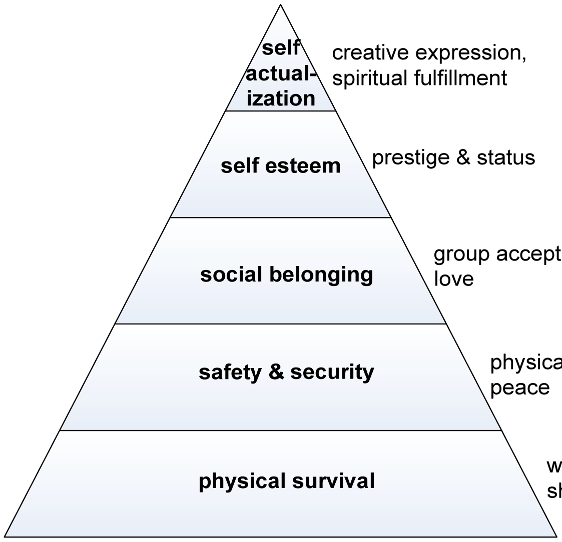

Figure 2. Maslow's hierarchy of needs.

PRIORITIES: 5•Ps

Distribution circuit owners are in the same boat, or rather, they should consider themselves stranded on the same metaphorical island as depicted in Figure 3. The first "P" at the base of the pyramid is "Post-failure." The highest priority has to be fixing cables that have just failed. There can be no doubt that these cables have the lowest reliability.

The second "P" is for "Problematic" cables. These are cables that have failed recently, but are back in service at the moment. Simply taking a cable out of service reduces its reliability – add thumping to the mix and the likelihood of a follow-on failure is much higher for this population of cables than any of the layers of the pyramid above.

The third "P" is for "Preemptive." These are cables, which are so expensive to repair or replace on an emergency basis that preemptive steps should be taken to avoid even a first failure. Submarine cables and cables feeding interruption sensitive industrial facilities exemplify this population.

The fourth "P" is for "Proactive." Many of these cables have failed; they all have splices, but there may not be complete records to indicate the reason for each splice. Many of the splices are from previous dielectric failures.

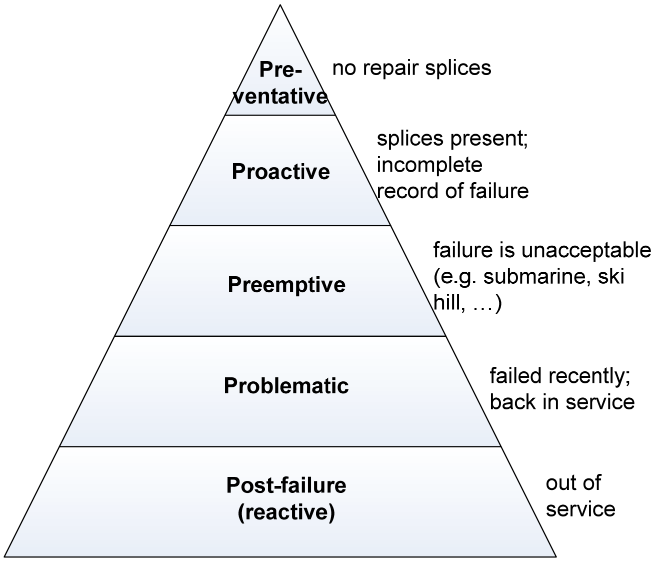

Figure 3. 5•Ps – distribution cable reliability hierarchy

Finally, at the top of the pyramid, the fifth "P" is "Preventative." These cables have provided perfect reliability up to this point, however they were installed at the same time using the same installation practices and have endured approximately the same environment as their sister cables, which may fall in the Post-failure, Problematic, or Proactive categories. Viewed through the prism of the 5•Ps, it is self-evident that this fifth population of cables should have the lowest priority for scarce resources. Ironically, these have been the most common category of cables to which silicone rejuvenation has been applied over the last two decades.

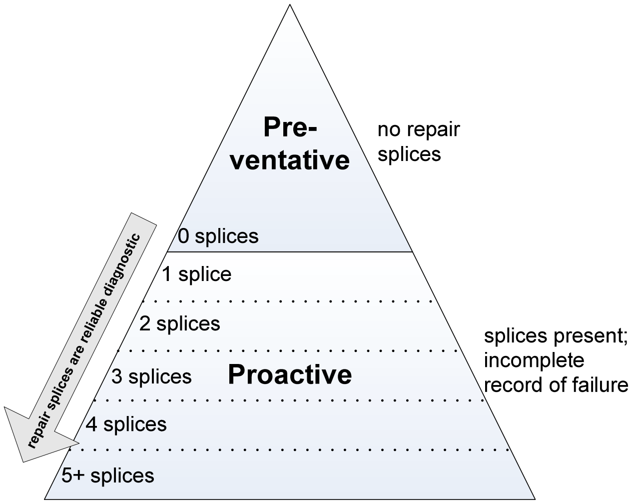

Figure 4. Prioritization within the top 2 "Ps". The number of splices may be a reliable diagnostic of the cable condition – the greater the number of splices the higher the priority within the Proactive trapezoid.

Focusing on just the top two levels of the pyramid (as illustrated in Figure 4) allows us to refine the prioritization for these cases. While the reason for the existence of an individual splice is often unknown, the presence of splices may be a sign of past reliability issues. The older methods of injection introduced about two decades ago and commercialized by the author and his colleagues, which depend upon flowing through existing splices, have improperly addressed the required bottom-up prioritization.

An improved method of injection, which was designed from the outset to address the distribution hierarchy of needs from the bottom up, was first introduced in February of 2006. Throughout this paper, the first generation injection approach will be referred to as ‘841, the last three-digits of the U.S. patent number [6], which generally describes its scope. The latest technology will be referred to as 732, to represent the group of pending patents [7], which define its scope.

The ‘841 approach as conceived was never intended to address Post-failure or Problematic cables. The ‘841 approach includes no provision for very rapid increases in dielectric performance [12]. There are no components to address partial discharge, absorption of UV photons emitted during the conversion of water trees to electrical trees, or voltage stabilization with known electron acceptors [3]. None-the-less, the approach was utilized by FPL to treat Post-failure and Problematic, but the results (provided later) were not encouraging.

The ‘841 approach was designed and was best suited to address the top of the distribution cable reliability pyramid in lightly loaded cables in cool mesic soils [2, 3]: Preventative injection with no splices – yes; Proactive injection with splices – yes and no. There are whole classes of splices through which fluid will not flow including: heat shrink, hand-wrapped, and most pin-and-socket splices [13]. Silicone splices (slip-on or cold-shrink) which come in contact with ‘841 fluid are destroyed [13]. For those molded EPDM splices which remain, some will flow and some will not; many will be damaged; all will absorb a portion of the fluid intended to treat the cable [13]. End-users of the ‘841 approach report about a 50% flow rate.

Referring to Figure 4, the injection success rate for Proactive (i.e. cables with splices) treatment is less than 50% – 50% for those cable sections with a single splice, 25% for those with 2, 12.5% for those with 3, et cetera. The unfortunate consequence is that those cables most in need of rejuvenation are either slated for replacement at considerable expense and often with considerable delay, or they are ignored entirely.

In contrast, the 732 technology appropriately focuses on cable with splices, replacing 100% of these weak links with the most modern and reliable technology available.

PROBLEM WITH PRODUCTIVITY PRICING

The productivity pricing paradigm was conceived and implemented about a decade ago by the author. The idea was to align the productivity and profit requirements of the supplier with those of the circuit owner. For example, as the circuit owner provided well-scoped projects and quick response on switching requests, the cost per injected foot declined at the same time as the profitability of the service supplier increased – a win-win scenario. The concept was benevolent in its intent, but the consequence of its widespread adoption has reinforced the inappropriate allocation of resources away from those cables most likely to fail to those cables least in need of rehabilitation.

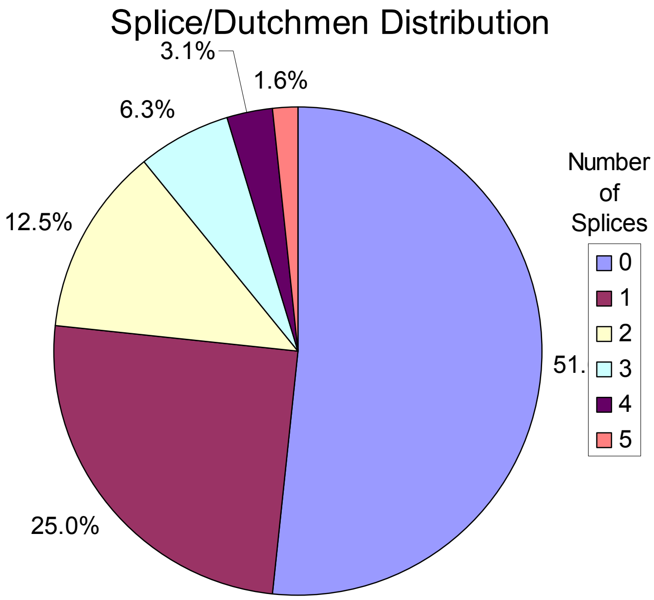

Figure 5. Typical distribution of splices in single phase URD circuits.

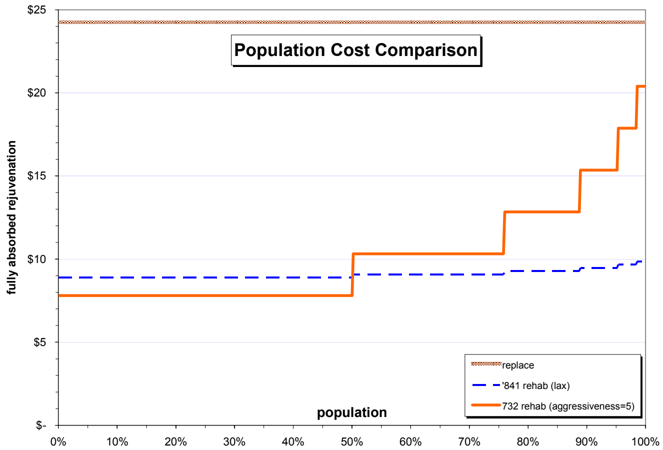

Figure 6. Typical cost escalation as the number of splices increase for rejuvenation approaches and replacement assuming that half of the splices encountered by the ‘841 rejuvenation approach flow and other half are abandoned.

Consider a typical distribution of splices in a 400-foot average length URD loop as depicted in Figure 5. Figure 6 shows the effect of multiple splices on the unit rejuvenation cost (i.e. the cost to treat) as the number of splices increase. At first blush, one might conclude that as the number of splices increases the productivity pricing model of the '841 approach provides the lowest first cost. That conclusion would be erroneous, however, because it ignores the cost to replace those cables which are abandoned to injection and must be replaced at considerably higher cost. The cost to test the cable and confirm that it does not easily flow is borne by the circuit owner, but there is little tangible return from that wasted activity.

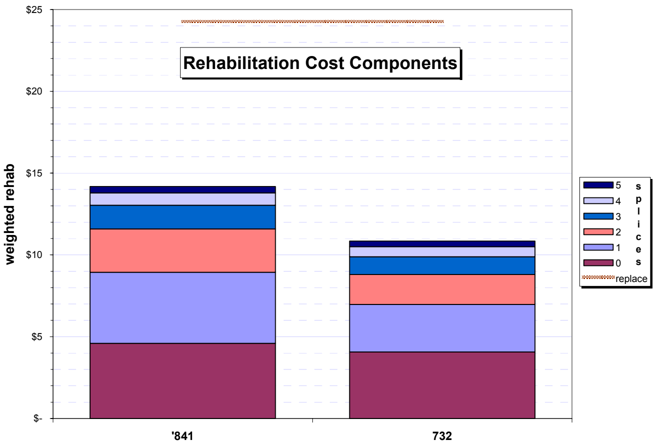

Figure 7. The cumulative rehabilitation costs are lower for the newer 732 method at any splice count because the cost of replacing cables abandoned with the old paradigm is much more than the cost to address the splices properly.

A more complete analysis is provided in Figure 7. Figure 7 shows the accumulation of all costs required to rehabilitate the entire circuit. To address the most unreliable cables, the circuit owner should encourage a pricing structure that assures that the profitability of the service provider does not suffer as the number of splices increase. The flat cost curve of the '841 productivity pricing paradigm illustrated in Figure 6 discourages the excavation of splices. Another unintended consequence of productivity pricing is created when the circuit owner provides incentives to its reliability managers to minimize first costs. When this occurs, both the service provider and the reliability manager are working together to ignore the most unreliable cables.

STRATEGIES: 3•Rs

Should the circuit owner Repair, Replace or Rejuvenate? Or more precisely, what combination of the 3•Rs should be employed? The simple answer is the circuit owner should employ the combination of strategies and tactics, which provide the maximum reliability with the greatest capital efficiency. Once the optimum strategy and tactical plan are established, it is largely an issue for senior management to determine the budget. The greater the budget is; the higher the reliability. It is a reality of the times in which we live that over spending by circuit owners is likely to go unrewarded by the rate payers, the utility commission, or, for investor owned utilities, Wall Street.

A complete accounting for the actual costs of each of these choices is the starting point for any analysis. Methods of assigning arbitrary overheads should be scrutinized to avoid having convenient rules-of-thumb promulgated by the finance department skew the optimization of resources. To illustrate the methods of this paper, Figures 8 and 9 present compilations of typical North American costs for each of the three strategies in U.S. dollars for a single-phase 1/0 AWG, 15kV direct-buried cable.

Element	Cost
Complaints	3 x $100
Troubleman restores power	$1,000
Dispatch utility locators	$500
Fault repair crew	$3,000
PUC performance-based ratemaking fine (or foregone incentive, goodwill, etc.)	$1,000
Total	$5,800

Figure 8. Compilation of failure costs. Overheads are included in each line item.

In addition to the assumptions in Figures 8 and 9, this paper assumes 11% as the discount factor and 3% as the inflation rate.

From the first cost perspective it is almost always cheapest to repair a cable, but there are two reasons that this "band-aid approach" is far from the optimum for pre-1980 vintage cables. First, there is about a 20% chance that the cable will simply fail again in the next 12 months [8]. There are numerous causes for this high "refailure" rate, but the transient voltages induced by the failure and those induced by the fault pinpointing process are notable and unavoidable. Second, only a couple of inches of cable on what is now a problematic cable have been removed. Even if the cable manages to survive more than a year, the reliability of this cable is suspect for the balance of its service life.

Rehabilitation Situation	Replace	Rejuvenate	
		'841	**732**
post-failure	$24.25	$9.00	$7.00
proactive or preventative	$24.25	$8.00	$8.00

Figure 9. Compilation of typical cable replacement and rejuvenation costs including all overheads for direct buried URD.

TACTICS: 4•Ts

Should the circuit owner Test, Treat, Tunnel or Trench? Or more precisely, what combination of the 4•Ts should be employed? The vast majority of the legacy cable, and hence the majority of the rehabilitation cost, is with small diameter underground residential distribution (URD) cable of the class used in our unfolding example. As demonstrated by [9], even if one assumes that diagnostic tests provide an indication of the remaining life of a cable, the economics appropriately dissuade its application to URD cables.

Even if diagnostic testing provided reliable results and even if it could be deployed at a low cost, viewed in light of the 5•Ps of Figure 3, diagnostic testing is of little value for the most important, bottom layers of the pyramid. One does not need a test to prove that the Post-failure cable currently out of service is a bad actor. Similarly, the Problematic cables, which have recently failed are almost certainly bad actors too. Because all diagnostic tests with the exception of online tests are inherently destructive, circuit owners should not utilize anything other than an online test of a Preemptive cable. If the technology has merit, its only value would be at the top of the *Hierarchy of Needs* pyramid (i.e. Proactive and Preventative) where it would have to compete for scarce O&M budget.

The cost savings realized by treating a cable rather than replacing it is generally 50% or more for direct buried cables even using the older '841 approach [10]. With advanced 732 technology and in light of the dramatic increase in the cost of cable driven by copper and aluminum prices, these savings can be realized for cables in duct systems too. As demonstrated by [10] the application of net present value analysis on the cash flows demonstrates the unambiguous economic superiority of treatment. This is not to say that cables should not be replaced. There are several reasons why replacement by tunneling or trenching must be utilized.

1. The ampacity of the cable is insufficient to meet growing demand. This is a rare occurrence for URD.
2. The neutral is completely gone. As demonstrated by [11], this occurs less than 1% of the time except in a few unlucky soil regimes (e.g. Wisconsin and Pennsylvania).
3. The number of splices or spot corrosion problems mitigates the economic advantage of treatment.

The first two cases are quite rare for URD cables. Systematic measurements of neutral condition on over 75 million feet of cable over the last two decades have shown that over 99% of URD cables fall outside of case 2 and over 90% have no significant corrosion. Not only do surveys and measurements on a large population of aged cables fail to identify neutral corrosion as significant, there has been no systematic study which demonstrates that the neutral corrosion issue is anything other than a red herring. There are no compelling engineering reasons to believe that a bare neutral that has survived intact for the last 30-40 years will not survive for another 30-40 years. Finally, neutral corrosion is inherently self limiting. Corrosion occurs because there is a difference in chemical potential between two portions of the same piece of copper. Assuming persistence of the condition (e.g. differential aeration, soil corrosion) which created the chemical potential difference, the corrosion proceeds until the circuit is broken – and then it stops as there must be a "metallic connection between the anode and cathode areas for electron current" [14]. This is why systematic surveys inevitably find the corrosion to be localized over just a few feet of exposed copper on the 10% to 15% of cables that have any significant corrosion at all. This localization makes repair a simple and inexpensive option. The neutrals are bridged with new copper and a magnesium sacrificial anode, sized to provide the desired life, is attached to the new copper in the precise location where the chemical potential difference is manifested.

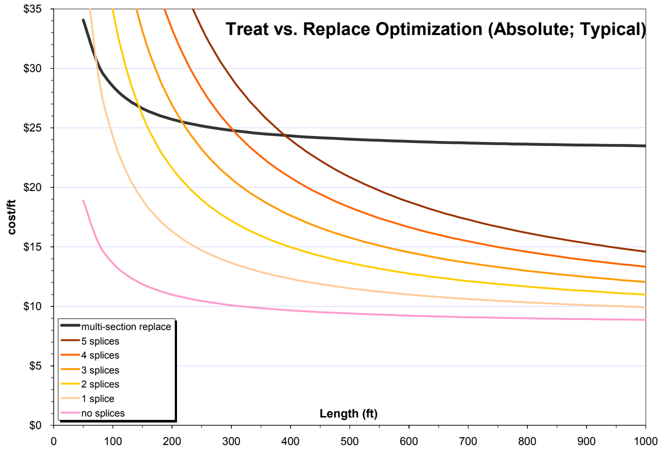

Figure 10. Many pits (splices or corrosion repair) can be excavated before rejuvenation becomes uneconomical.

The third case deserves a more detailed view and brings us back to the top two Ps illustrated in Figure 4. How many pits should be excavated when treating cable before it is preferable to replace the cable? In [10] that question was answered for the older '841 technology, but 732 technology with life extension equal to new cable requires a refinement of that approach. The 732 injection paradigm, which requires only a single visit to a cable segment confers a significant economic advantage. It is almost always less costly to excavate direct buried splices than it is to try to flow through them. The cost savings of not having to visit the same cable segment at least three times is greater than the cost of excavating and replacing splices. Figure 10 uses the typical cost structure introduced above and utilized throughout this paper. It shows the relationship between the cost to replace (black line) and the cost to rejuvenate with 732 technology (colored lines) for zero through 5 splices as a function of the cable segment length. For a 400 foot segment of cable, it is typically economically advantageous to excavate 4 repair pits. These old splices are potential failure points and, as indicated by the arrow in Figure 4, a predictor of future problems.

BATHTUB CURVE

The life of a cable, just as the life of many things, may be represented by the so-called bathtub curve, so named because of its characteristic shape. The life time of the cable is disassembled into three time realms. First is the infant mortality realm, where the rate of failure is decreasing with time. Next is the constant (random) failure realm, where the failure rate neither goes up nor down, but is characteristically low. Finally, the third realm is often referred to as the wear-out period and is characterized by an increasing failure rate. The combination of these three realms defines the foot, the bottom, and the back respectively of a bathtub cross section. Just such a bathtub curve is presented as Figure 11, which was fit to the data of Figure 1 using the Weibull probability density function of equation (1).

$$(k/\lambda)(x/\lambda)^{(k-1)}e^{-(x/\lambda)^k} \qquad (1)$$

Where x is the time, λ is the scale factor, and κ is the shape parameter. Values are $\lambda=1\text{x}10^{21}$, $7.5\text{x}10^4$, $5.7\text{x}10^2$ and $\kappa=0.1$, 1, 4 for infant mortality, constant failure, and wear-out failures respectively.

The x-axis of Figure 11 begins 25 years ago (i.e. -25) when the cable was first installed and advances to year 0, which represents today. The shape of the Figure 11 bathtub is a bit cramped for the metaphorical bather, because the constant failure period of pre-1980 vintage cables was disappointingly brief.

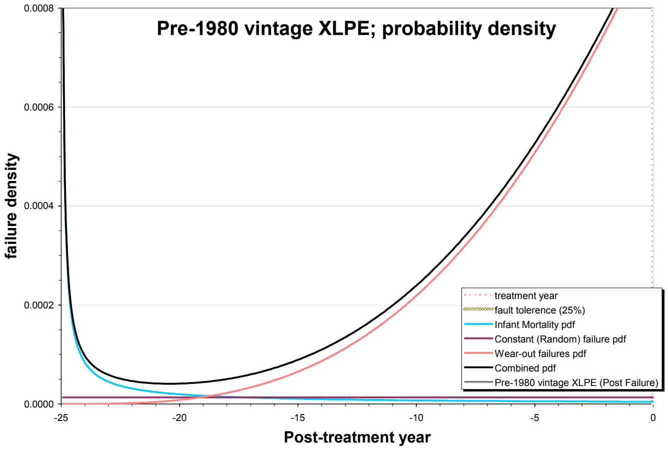

Figure 11. Bathtub curve (black) for typical pre-1980 vintage No.2 cable is the sum of three Weibull components (Eq. 1): infant mortality (cyan), constant failure (plum) and wear-out failure (rose).

The failure density function of equation 1 and its representation in Figure 8 are not as useful as the cumulative failure distribution defined by equation 2 and illustrated by Figure 12.

$$1-e^{-(x/\lambda)^k} \qquad (2)$$

In this view the same three Weibull functions (representing infant mortality, constant failures, and wear-out failures are represented by cyan, plum and rose colored lines respectively) sum to the black line which begins at 0% failure on the day of installation 25 years ago and ends at 100% population failure about 65 years later. This cumulative distribution assumes that the failed cable is rehabilitated when it fails. If instead, the failure is spliced and the cable is left in service, it will likely follow a cumulative failure path similar to the grey line. The diamond in Figure 12 is a data point representative of the Figure 1 failure data. The triangle represents a 20% "re-failure" rate reported by Florida Power and Light (FPL) for cables repaired and placed back in service.

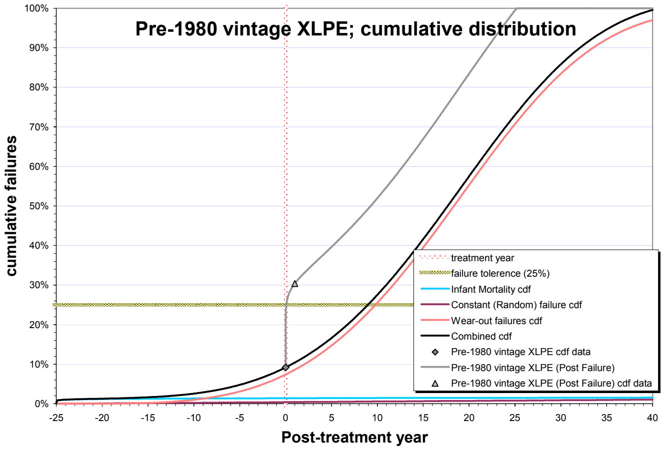

Figure 12. Cumulative failure view of bathtub curve showing mounting failures over a 65 year time span.

Each circuit owner must decide its failure tolerance based upon the capital resources available to it and its reliability requirements whether self imposed or imposed by a regulatory authority. In Figure 12, that failure tolerance is assumed to be 25%. That is, the circuit owner will rehabilitate all remaining cable in the population of cables once the failure tolerance is exceeded.

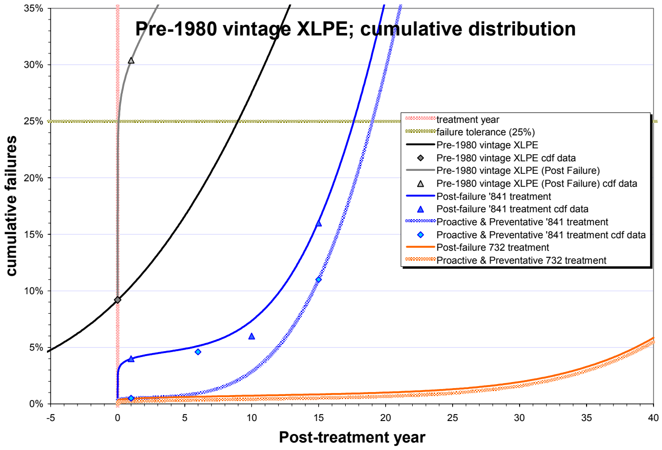

Figure 13. Data and models of Figure 12 along with data and models for post-treatment performance for '841 and 732 technology.

Figure 13 provides post-treatment performance data and models which can be used to interpolate and extrapolate the post-treatment performance of cables in the population of pre-1980 vintage, URD cables buried in hyperthermic soils (Phoenix, Texas, and Florida). The data represented by blue triangles are FPL post-injection performance utilizing the '841 technology to treat cables immediately after failure (i.e. Post-failure). The data represented by blue diamonds are FPL post-injection performance utilizing the '841 technology to treat cables Preventatively and Proactively. Both data sets include 15 years of experience from the largest user of silicone injection technology. As described in detail in [2] and [3], circuit owners with lightly loaded cables in cooler soils may anticipate better performance than that experienced by FPL.

The 732 technology was introduced in February of 2006 and has been utilized in thousands of cables spread across two continents and in all 5•Ps. Since there have been only a few dielectric failures of a 732 rejuvenated cable to date, it is not possible to provide statistically significant data to fit post-732-treatment bathtub curves. Lacking a statistically significant failure rate, the post-treatment 732 models of Figure 13 utilize the Weibull parameters established by the older '841 technology and adjusts them to realize the minimum 3.5-fold long-term improvement demonstrated by accelerated laboratory testing in [2] and [3] and the up to 87-fold faster increase in performance demonstrated in [12], which significantly reduces the infant mortality.

REVISITING 3•Rs

The question of Repair, Rejuvenate or Replace can now be definitively addressed utilizing the economic assumptions for the typical case described above, and the post-injection performance models, which were fit to data from two large North American utilities. It is now possible to perform a net present value analysis on a wide variety of potential strategies and tactics. To illustrate the method consider 7 potential strategic and tactical combinations to deal with 500k feet of failing pre-1980 vintage URD cable. For this example, assume the average segment length is 400 feet and that there are 1,250 cable segments. A legacy of 9.3% of those segments, or 116, has failed to date. The 25% failure tolerance is reached when the total failures reach 312 (25% of 1,250 segments). For rehabilitated (treated or replaced) cable populations the legacy failures are ignored – in other words after rehabilitation the circuit owner expects the population to have a high reliability within the planning horizon.

1. Base case – replace after failure. Replace fault-free cables when 25% fault tolerance is exceeded.
2. Proactively and Preventatively replace all 500k feet.
3. Repair on first failure; replace on second failure. Replace fault-free cables when 25% fault tolerance is exceeded.
4. Post-failure rejuvenation with '841 – replace on re-failure. Replace fault-free cables when 25% fault tolerance is exceeded.
5. Proactively and Preventatively rejuvenate with '841. Replace fault-free cables when 25% fault tolerance is exceeded.
6. Proactively and Preventatively rejuvenate with 732. Replace fault-free cables if 25% fault tolerance is exceeded.
7. Post-failure rejuvenation with 732 – replace on re-failure. Replace fault-free cables if 25% fault tolerance is exceeded.

For cases 1 and 3, an incremental 196 failures (i.e. 312 tolerated faults less 116 legacy faults) are tolerated before the entire population is replaced. For case 2, 4, 5, 6 and 7 the expectations of the circuit owner are reset within the planning horizon and hence 312 failures (25% of the population) may be tolerated before the cables are rehabilitated a second time. The example generously assumes that replaced cable has no failures over the entire planning period and ignores warranties.

Strategy	Outages	Unit Net Present Cost	Net Present Cost per Avoided Outage
1. Replace failures	196	$13.02	
2. Proactive replace	0	24.25	$ 28,634
3. Repair & replace	196	24.19	none avoided
4. Post-failure '841	311	17.04	deferred
5. Proactive '841	312	14.69	deferred
6. Proactive 732	69	8.25	(18,686)
7. Post Failure 732	73	7.36	(23,018)

Figure 14. Economic and reliability comparisons of seven strategic and tactical combinations for typical URD cable.

Figure 14 summarizes the results and demonstrates the difference between a deferred outage and an avoided outage. Treating URD cable with the '841 approach in hypothermic soils or moderate to heavily loaded cables defers the outage by perhaps a dozen years as first predicted in [2] and [3] and confirmed with end-user experience. Since the planning horizon for that type of treatment is typically 20 years, the outage still occurs and the electrical end user is still inconvenienced. There remains some economic value in the '841 approach because it allows the circuit owner to defer the failure costs and the larger capital expenditure associated with replacing, but the base case strategy of simply replacing each failed cable immediately after failure is generally superior both economically and in the total number of outages.

The economic and circuit reliability outcome is entirely different if the technology is able to extend the life of the cable beyond the planning horizon. With a minimum of 3.5 times the life-extension performance of the two-decade old '841 approach, the 732 technology provides a coveted triple-play.

1. The first costs, including the cost of splice replacement and neutral repairs, are the lowest of all of the alternatives.
2. The total outages experienced are the lowest possible short of the capitally intensive wholesale replacement option.

3. The economics are superior by two measurements. First, the unit net present cost is about half of the next closest strategy, namely replace after failure. Second, the cost per avoided outage is *negative*. In other words, there are net present value *savings* per avoided outage. This occurs, because the avoided costs of the outages more than offset the costs of the 732 rehabilitation strategy when all costs are returned to a present value basis. This is true for both the 732 Proactive and Preventative strategy and for the 732 Post-failure strategy.

SUMMARY

The 5•Ps of distribution cable reliability coupled with the latest rejuvenation technology circumvent the old rules of the zero-sum-game, which pitted the circuit owner against the electrical customer and the regulator. Financial considerations of the underground distribution circuit owner and reliability needs of its customers are harmonized, when a circuit owner applies capital to the base of the pyramid first and utilizes the most advanced technology available. In fact, there is a both a net savings realized from the application of 732 rejuvenation technology *and* a net reduction in the number of interruptions. This net cost savings *and* net reduction in interruptions eliminates the zero-sum-game that the industry has been trapped in for over two decades. In contrast to the outage *deferral* of the two-decade old '841 approach, the 732 rejuvenation technology allows cables throughout the entire pyramid and especially those at the bottom to *avoid* outages during a very long post-rehabilitation planning period. Armed with capital-effective outage avoidance technology the utility and its non-customer stakeholders enjoy economic and operational advantages, while at the same time satisfying the desire of the electrical customer for reliable and inexpensively distributed electrical power.

The models described by this paper are available from the author and may be customized to reflect each circuit owner's unique circumstances. For those circuit owners that have used '841 injection, post-injection performance history is available from the website of the '841 supplier.

REFERENCES

1. Forrest, "Predicting Medium Voltage Underground Power Cable Failures and Replacement Costs," Western Electric Power Institute, Underground Distribution Workshop, April 8, 1997.

2. Bertini, "Accelerated Aging of Rejuvenated Cables – Part I", ICC, Sub. A, April 19, 2005.

3. Bertini, "Accelerated Aging of Rejuvenated Cables – Part II", ICC, Sub. A, November 1, 2005.

4. Bertini, "Death by 1000 cuts", ICC Spring 2000 minutes pp 162-163.

5. Smith, "Aged equipment sends a jolt through strained power industry", The Wall Street Journal, 08/18/2006, p. Al.

6. Bertini, Vincent et al, "Method for enhancing the dielectrical strength of a cable using a fluid mixture", U.S. Patent 5,372,841.

7. 732 and related technologies have patents pending including published U.S. applications 2005/0191910, 2005/0189130, 2005/0192708, the PCT equivalents and other unpublished applications.

8. Private communication from FPL with author.

9. Bertini, "Diagnostic Testing and Deferral Economics", Minutes of the Spring 2001 ICC, pp. 123-138.

10. Bertini, "Recent advances in cable rejuvenation technology" 1999 IEEE PES Summer Meeting, 7/99.

11. Gurniak, "Neutral Corrosion Problem Overstated Recent study suggests problem may not be as serious as once thought", Transmission & Distribution World, Aug 1, 1996.

12. Bertini, "New Developments in Solid Dielectric Life Extension Technology", IEEE ISEI, Sept. 2004.

13. Bertini, "Improving Post-treatment Reliability: Eliminating Fluid-Component Compatibility Issues", ICC C26D, Nov. 2005.

14. IEEE P1617/D5.0, "Draft Guide for Detection, Mitigation and Control of Concentric Neutral Corrosion in Medium Voltage Underground Cables", Cable Neutral Corrosion Working Group, ICC, 4/2005.

AUTHOR

Glen J. Bertini is CEO of Novinium, Inc., the world leader in cable rejuvenation technology. He has spent the last two decades working with cable injection beginning with its development at Dow Corning in 1985 and continuing through its commercialization and growth to over 75 million feet of cable rejuvenated to date. Mr. Bertini is the world's foremost authority on the business and technology of cable rejuvenation. Mr. Bertini holds a total of 16 patents on cable rejuvenation and related technologies and has 7 more pending. In 1992, he was co-recipient of the prestigious R&D 100 award for cable rejuvenation. Mr. Bertini was employed by Dow Corning, a silicon chemical manufacturer, and later UTILX where he was instrumental in the development and commercialization of the first ('841) cable rejuvenation product. Mr. Bertini holds a B.S. in Chemical Engineering from Michigan Technological University and is a Senior Member of the IEEE and a Voting Member of the ICC.