Silicone Injection: Better with Pressure

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***Abstract*: Moderate pressure injection has been utilized for over two decades and has demonstrated several significant advantages over the low pressure inject-and-soak paradigm. In 2006 sustained moderate pressure injection further advanced rejuvenation technology, increasing post injection reliability.**

This paper traces the evolution of injection pressure in dielectric enhancement technology and compares the merits of the available delivery methods. The paper goes on to introduce the latest improvement in injection technology, thermally enhanced rejuvenation.

INTRODUCTION

From 1984 through 2008, over 80 million feet of medium voltage underground power cable have been treated with available injection technologies. Over the last two decades, the fluids used to treat the cables have changed, and so too have the mechanical methods utilized to deliver the fluid into the strands. The fluid changes were described in detail in [1] and [2]. This paper focuses on the improvement of the mechanical process since 2006. Improvements include a new sustained pressure rejuvenation paradigm (SPR) introduced in 2006, and the 2008 introduction of thermally enhanced rejuvenation (TER).

There must be some driving force to transport fluid down the tight interstitial spaces between the strands of a stranded conductor. That driving force is a pressure gradient from a feed source to an outlet. The flow of rejuvenation fluids through the small interstitial spaces between the strands of power cables is entirely laminar and hence is described by Poiseuille's law.

$$\frac{dV}{dt} = \frac{\pi R^4}{8\eta}\frac{|\Delta P|}{L} \qquad [1]$$

In Equation 1, dV/dt is the volumetric flow rate, η is the dynamic viscosity, ΔP is the pressure driving force, L is the length of the cable, and R is the hydraulic radius of the strand interstices. The geometry of the cable, its interstitial shape, and its length were determined by the design of a cable, which was engineered and installed decades ago. The manufacturer of the cable and the engineer who determined the length of the cable did not make any allowances to facilitate the injection of the cable when it approached the end of its useful life. At first glance the injector appears to have three variables to manipulate the delivery of fluid to the strands – the pressure gradient, ΔP, the viscosity, η, and the time, t.

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ICC SubA, May 19, 2009

A more expansive consideration of the variables suggests that it might be possible, even after the fact, to change the hydraulic radius of a cable. This paper will discuss each of these four variables and their implications on performance. Performance considerations include the time to inject, which impacts the safety and economics of the process, and the post-injection reliability of the circuit.

INJECTION TIME

Since most URD cables have historically been injected while energized, injection time generally did not impact circuit availability. Furthermore, most circuits in North America are less than 200 meters (656 feet) in length, where patience allows these cables to be injected without the use of moderate pressure or moderate temperature. For two decades there appeared to be little incentive to shorten the injection time. As described in [3], longer cable lengths, such as those commonly found in submarine applications, present an additional technical challenge. The chemical reactions that occur with silane treatment fluids can increase the fluid viscosity in the strands during prolonged injection periods and prevent the successful injection of fluid along the entire cable length. This issue is beyond the scope of this paper, and was discussed in great detail in [3].

Aside from the case of very long cables, there had been no obvious economic reason to shorten the injection time. Reinforcing the *status quo*, go-slow approach, the necessity of 60 to 120 day soak periods after the completion of injection provided little incentive to accelerate the injection process. What is the difference between an injection that takes 30 minutes and one that takes 3 days, if each is appended with a 60 day soak period? On a percentage basis 5% or less of the time would be gained.

The introduction of sustained pressure rejuvenation (SPR) has changed this indifference to injection time for two reasons. First it was discovered and described in [4] that increased pressure improves the dielectric performance of injection fluids, and that this improvement, together with certain chemical improvements described in [1] & [2], allowed the elimination of the soak period. Elimination of the soak period has a significant impact on the economics of rejuvenation. The largest portion of the cost to inject cable is the cost of the highly skilled labor required to deliver rejuvenation. While elimination of the soak period obviously reduces cost, it also changes the impact of the 30-minute-versus-3-day injection time posed in the previous paragraph. Instead of 5% or less, the impact is now much greater. Minimizing injection time is now of prime economic importance.

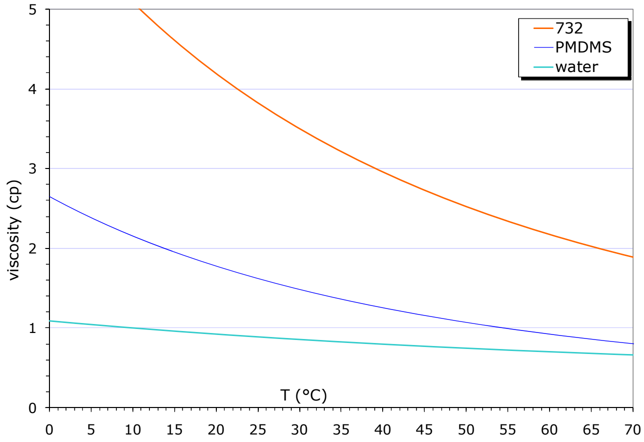

Figure 1. Viscosity as a function of temperature for 732 fluid, PMDMS (phenylmethyldimethoxysilane), and water. Viscosity decreases with increasing temperature.

VISCOSITY

The fluid flow rate (dV/dt) in equation 1 is directly proportional to the reciprocal of the viscosity. That is a doubling of the viscosity reduces the flow rate by a factor of two; the time spent injecting a given cable length at a given temperature and pressure doubles. Therefore, the engineer creating a rejuvenation formulation is constrained in the choice of materials, because the fluid viscosity must not be too high. On the other hand, many compounds, which might provide benefits to power cables, have higher viscosities and hence an engineering tradeoff is required. Chemical components that provide partial discharge suppression, ultra-violet stabilization, voltage stabilization, and anti-oxidation to modern rejuvenation fluids, included in the fluid coded as 732 in Figure 1, have higher viscosity than the monomeric silane, PMDMS also shown in Figure 1, which was introduced over two decades ago and does not include those advanced functions. Before leaving the subject of viscosity, it is important to note that liquid viscosity decreases as the temperature increases. All other things being equal, fluid flow at low temperatures will be slower than at higher temperatures. We will revisit this observation later in this paper.

ΔP

There are three pressure ranges commonly used to inject medium voltage polyethylene cable – low pressure, which is less than 50 psig and generally less than 20 psig, moderate pressure, which is 50 to 500 psig, and high pressure, which is between 500 to 1000 psig. EPR cables have much lower hoop strength than polyethylene (PE, whether HMWPE, XLPE, TRXLPE, or copolymers of PE), and are generally only injected at low pressure. The balance of this paper focuses on PE cables only, but the principles are the same for all solid dielectric insulated cables.

Table 1. AEIC Test number 582 results of AC breakdown on 1/0 XLPE cables filled at various pressures from [5]. There is no adverse consequence of pressure up to about 1000 psig.

Fill Pressure (psig)	High Voltage Time Test (volts/mil)
Control (0)	806
500	856
750	1071
1000	1018

The earliest *in situ* injection approaches first used in the mid-1980s were limited to the maximum pressure, which could be confined by molded terminations and splices. This injection paradigm is called unsustained pressure rejuvenation (UPR). The interference fit of such accessories for small diameter cables can typically withstand internal pressure of 20 to 30 psig. As the diameters of the cable and the accessories increase, the maximum leak-free internal pressure declines rapidly. For cables larger than 107.2 mm^2 (AWG 4/0), a gauge pressure just slightly above zero will typically cause a leak along the interface. Such a leak is unacceptable because fluid, which is meant to treat the cable, is lost and the splice is quite likely to fail as fluid may transport contaminants along the leak path. Cables naturally have elevation changes along their length, and just the head pressure caused by these elevation changes can exceed the containment capability of accessories.

High pressure injection was utilized on new cables in the late 1980's as a method to strand fill cables, while they were on their shipping reels at the factory. This approach was patented in 1989 (filed in 1987) as disclosed in [5] and utilized commercially for some time by Hendrix Wire and Cable discussed in [6]. The introduction of fluid at high pressure demonstrated a significant improvement in dielectric performance as demonstrated in Table 1 when the cables were subjected to AEIC Test number 582. While high pressure injection is typically not utilized in field applications, its use for on-the-reel injections demonstrated that there are no adverse consequences to the cable performance up to about 1000 psig for an unaged 1/0, 15kV cable.

Beginning in the 1990's moderate pressure injection was widely adopted. The first uses were for very long submarine applications. For example in October of 1998, a 1/0 cable to Kelly's Island in Lake Erie was injected at 400 psig requiring about 10 days to complete the injection phase. The approach was also used on shorter cables segments, which did not have splices. This moderate pressure inject and soak approach has been applied on thousands of cable segments for over 15 years. According to [7], [8], and [9], moderate pressure injection of 340 to 500 psig over that period have been routine. In [9] for example, it is disclosed that, "[one rejuvenation supplier] has for years treated power cables with pressures … sometimes even exceeding 500 psi."

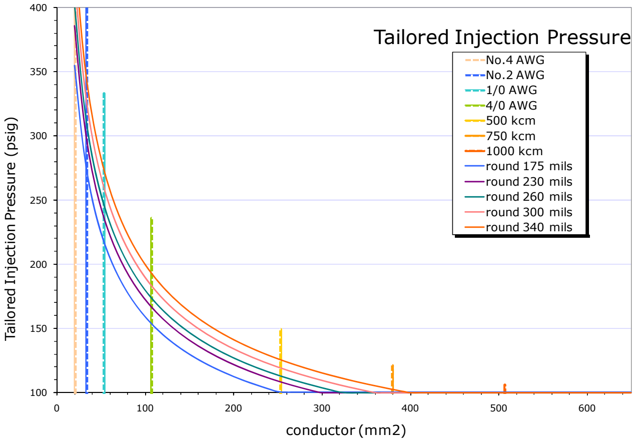

Figure 2. With SPR injection the pressure is tailored to the unique circumstances of each individual cable. The moderate pressures are less than those, which have been historically used.

Sustained moderate pressure rejuvenation (SPR) became possible in 2006 with the introduction of patented injection adapters described in [10] and [11], which can permanently seal fluid within the strands. SPR has dramatically improved post-treatment performance, as demonstrated in [4]. The moderate pressures utilized with the patent pending SPR process are lower than the pressures routinely utilized before the introduction of SPR as shown for example in [8] and [9]. The tailored injection pressures utilized for SPR are shown for round-strand PE cables in Figure 2. The word “sustained” in SPR, defines the difference between the older, moderate pressure injection process and the newest approach.

Even though moderate pressure injection periods of 10 or more days for submarine cables were common with the old approach, once the fluid flowed through the entire length of the cable, a portion of the just-injected fluid was bled off to yield a much lower soak pressure, typically less than 10 psig. By contrast, SPR does not bleed off already injected fluid to lower the pressure in the cable. Instead, the fluid is trapped inside the cable when the injection is complete, and the pressure decays as that trapped fluid permeates radially outward into the insulation.

Figure 3 shows a typical pressure decay curve for a 1/0 15kV cable injected at 240 psig with SPR. The total time with residual pressure is less than 10 days – on a par with the amount of time pressure was held on the previously cited submarine cable on the floor of Lake Erie in [8]. In the three years since SPR was introduced, thousands of cables have been successfully injected. The actual post-injection failure rate for cables proactively treated with SPR is about half of the reported failure rate for non-SPR proactively treated cables and is displayed in Figure 4. Because SPR provides superior post-injection reliability, it should be applied wherever possible.

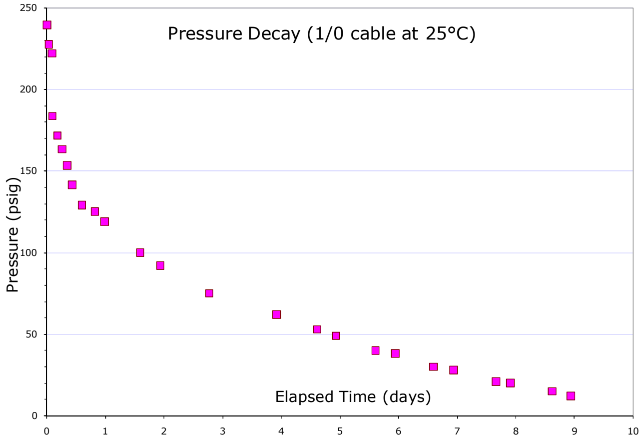

Figure 3. Typical pressure decay profile on a 1/0 15kV cable at 25°C.

The tailored injection pressure (TIP) utilized to inject a cable within the SPR paradigm varies with several factors. The two most important of those factors are shown graphically in Figure 2 – strand geometry and insulation thickness play a large part in determining the optimum SPR injection pressure. Strand compression, the temperature, and the cable dielectric material also play roles.

ELEVATED PRESSURE EFFECTS

The most obvious effect of elevated pressure, especially sustained elevated pressure, is improved post-injection reliability. Figure 4 shows a Crow-AMSAA plot of all post-injection failures for all causes, since SPR was introduced over three years ago in February 2006. The application of Crow-AMSAA in electrical cable reliability is discussed in [12]. The slope (or β) obtained by least squares is 0.43. A value less than 1 indicates a declining failure rate. A slope of 1 signifies a stable failure rate, and a slope greater than 1 represents an increasing rate of failure.

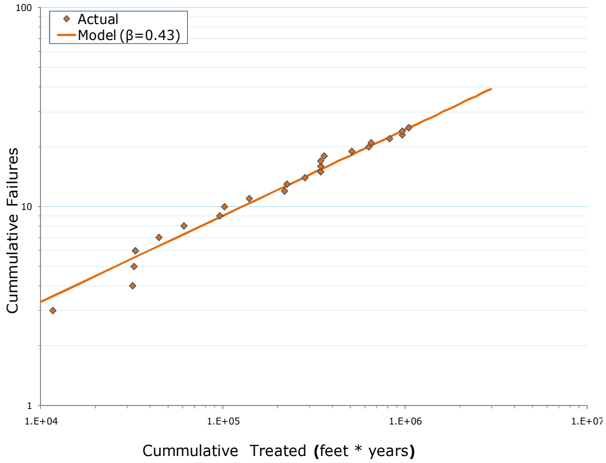

Figure 4. Actual post-injection failures experienced with SPR as of April 1, 2009.

Table 2. New Orleans 7-day XL treatment experiment from [13] demonstrates higher pressure treatment outperforms lower pressure treatment.

Sample	63% AC break down	Fluid Usage (lbs/kft)
Untreated control	55.5 kV	
XL treated @ 30 psig	63.5 kV	17.1
XL treated @ 117 psig	74.5 kV	33.7

In yet another experiment described by [13] utilizing fluid coded as XL, which is a mixture of phenylmethyldimethoxysilane and trimethylmethoxysilane, a 750 kcmil 15kV feeder cable from New Orleans was treated with the same fluid at two different pressures, 30 psig and 117 psig. Seven days after the treatment, the injected test cables and their untreated control were divided into 6 lengths each and sacrificed to AC breakdown. The results are summarized in Table 2. The sample injected at the higher pressure absorbed twice the fluid and had about twice the increase in AC breakdown performance compared to the identical sample, treated with the identical fluid, at the lower injection pressure.

Sustained moderate pressure injection provides improved reliability compared to lower pressure injection methods, but is there a pressure that can be too high? Two experiments provide insight. The fist experiment depicted in Figure 5 shows the relationship between the outside diameter (OD) increase (expressed as percent deflection) of a 1970s vintage 1/0, 175 mil HMWPE insulated cable as the interstitial pressure was raised in 50 psi steps from 0 to 750 psig. Each pressure setting was held for 15 minutes before proceeding to the next pressure step. Each diameter was measured in two locations with a laser micrometer is shown in Figure 6. The two values were averaged.

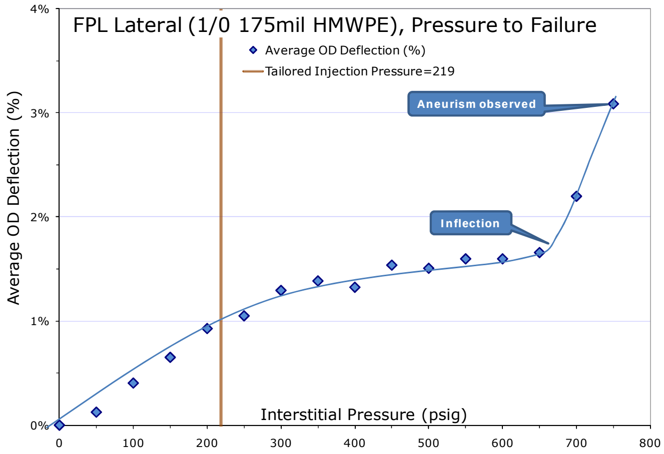

Figure 5. Pressure test to failure undertaken at FPL laboratory. Interstitial pressure was increased 50 psi at 15 minute intervals until the cable developed an obvious aneurism at 750 psig.

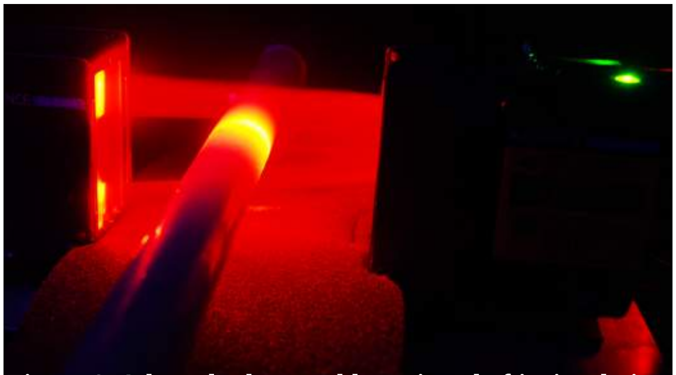

Figure 6. A laser bathes a cable, stripped of its insulation shield. The shadow cast upon the photo detector array is measured with an accuracy of ±0.05 mils.

The 175 mils of aged HMWPE has close to the lowest possible hoop strength of any polyethylene cable design and represents a close to worst case scenario. There are three discernable regions in the model curve of Figure 5. At pressures below 300 psig the OD deflection is linear and is less than about 1%. Over the pressure range of about 300 to 600 psig, the OD deflection is parabolic, with decreasing slope and is less than 1.5%. At pressures greater than about 650 psig an inflection occurs and the OD deflection becomes hyperbolic, with increasing slope and is greater than 1.5%. This third region is where bonds are broken and irreversible damage occurs. The tailored injection pressure utilized by the practitioners of SPR is 2-times to 3-times lower than the hyperbolic inflection point.

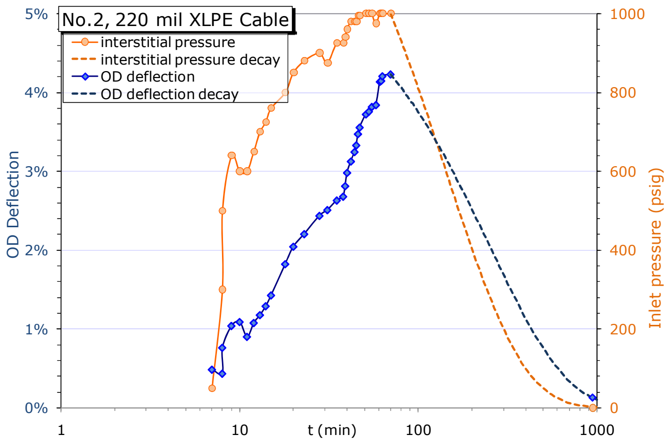

Figure 7. Diameter recovery as interstitial pressure decays in a rejuvenated cable at room temperature. The pressure was increased gradually to 1000 psig over the course of 70 minutes and then allowed to decay. The deflection of the outside diameter as a percentage of the insulation diameter is shown by the diamonds and the left axis; the interstitial pressure is shown by the circles and the right axis, each to a logarithmic x-axis in time.

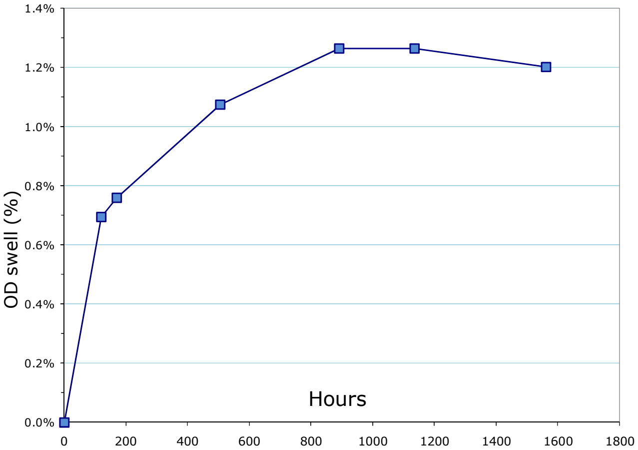

Figure 8. Polymer swell expressed as a percentage of the cable diameter of a 1/0, 175 mil XLPE insulated cable fully immersed (inside and out) with acetophenone at 22.7°C and zero gauge pressure. The cable becomes fully saturated at about 1000 hours.

Figure 7 shows a second experiment with a contemporary No.2, 220 mil XLPE insulated cable. The pressure was raised over the course of 70 minutes to 1000 psig and no hyperbolic inflection was observed. The thicker, unaged, and cross linked polyethylene is more resilient than the worst case cable depicted in Figure 5. The interstitial pressure was sustained and allowed to decay at room temperature as the rejuvenation fluid permeated into the cable insulation. Over the course of the next 900 hours the pressure decayed to zero and the OD deflection decayed to 0.13%.

Some level of OD deflection is anticipated by polymer swell as the rejuvenation fluid permeates into the conductor shield and insulation. Figure 8 shows the level of OD deflection when a sample of cable is fully immersed, inside and out, in acetophenone. The 0.13% level of residual deflection depicted in Figure 7 is consistent with the anticipated OD deflection from treating the cable from the inside only at any injection pressure after about 1000 hours.

Of the population of cable subsegments to which SPR has been applied since it was introduced 37 months ago utilizing the tailored injection pressure (TIP) illustrated by Figure 2, less than 0.05% (less than 1 in 2000) have experienced a burst during injection. In all such cases, the reason that the cable was unable to withstand the pressure was traceable to a cable defect. Figure 9 shows such a defect taken from a burst cable. The insulation is eccentric and not a good candidate for rejuvenation, because it does not meet the ICEA S-97-682-2004 minimum insulation thickness. Such eccentricity is rare as evidenced by the extremely low failure rate – 99.95% injected without eccentricity defects. Moderate pressure injection is an effective diagnostic for the occasional eccentric defect, as the burst occurs while the cable is not energized and can be easily repaired.

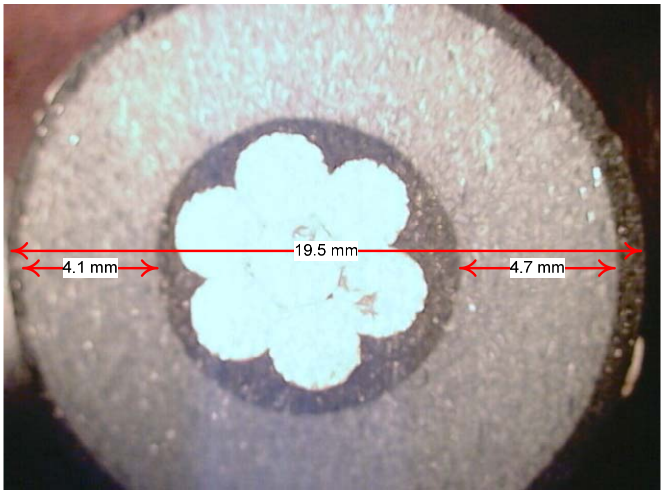

Figure 9. Enlarged cross section of a cable, which burst at its tailored injection pressure (TIP). The cable was eccentric along a significant length. This photograph was taken 72 cm from the burst point. The minimum insulation thickness is less than the 4.19 mm minimum insulation thickness required by Table 4-7 of ICEA S-97-682-2004. Note that the strand-shield remains in intimate contact with the strands.

Expansion and contraction of the diameter of an in-service cable and mechanical stresses at the interfaces between layers of its construction are normal occurrences, which the cable is designed to accommodate. For example, Figure 10 provides measurements of how the outside diameter (OD) of a URD (underground residential distribution) cable varies as the temperature is raised from about 15°C to 130°C. The diameter measurements were made with a laser micrometer as shown in Figure 6, the conductor temperature measurements were made with a thermocouple implanted in an identical control cable in series with the test cable, and the insulation exterior temperature was measured with an infrared thermometer. When the conductor reaches 90°C the OD deflection is about 1%, which is a typical OD deflection encountered with SPR injection. At 130°C the OD deflection is about 2%.

Polyethylene has a coefficient of linear expansion of about 129×10^{-6} m/m °K; the values for aluminum and copper are 22.2×10^{-6} m/m °K and 16.6×10^{-6} m/m °K respectively. The ratios of thermal expansion are 5.8 and 7.8, for aluminum and copper respectively, compared to the polymeric strand shield and insulation. As the cable experiences thermal expansion and contraction differential radial movement between the metallic conductor and the polymeric shield are inevitable. The conductor and the shield necessarily separate and slide, one upon the other. This constant interfacial movement from thermal cycling is the cause for the phenomenon of cable shrink back. There is no chemical bond between the conductor and the shield, nor would one be desirable.

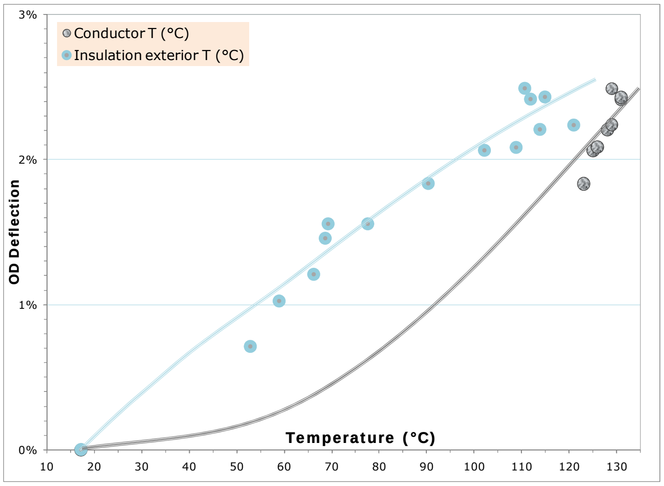

Figure 10. The outside diameter of a 1/0 175 mil XLPE insulated cable varies a couple of percent with normal load cycling.

This relative motion and the transient gaps the motion creates do not interfere with the performance of the conductor shield, because the interface between the conductor and shield lies entirely within the equipotential semi-conductive shield. Hence there are no potential gradients, as long as the conductor makes occasional and regular contact with the shield. As evident from the Figure 10 scale drawing, it is difficult to imagine a circumstance where a 1% or 2% radial deflection could impact the electrical contact between the conductor and shield, when the typical depth of the "valley" between two adjacent conductor strands is on the order of 9.5% of the outside radius of the insulation. Both thermal cycling and moderate rejuvenation pressures create deflections one-third or less of the depth of the inter-strand valley. It is not possible for a conductor shield "peak" to withdraw from an inter-strand valley. Even greater comfort can be had when one considers the axial direction not depicted by the two-dimensional view of Figure 10. Along that axis the strands are twisted; disengagement around the entire irregular circumference is simply not possible at conductor temperatures up to 130°C and at the moderate pressure used to rejuvenate cable. Finally, gravity ensures that the strand shield must be in contact with the strands at least at a single point around the circumference. Not only is temporary disengagement of the strand from the strand shield not possible, the adaptors described in [10] utilized to inject cables with the SPR paradigm are designed specifically to eliminate any risk of cable shrink-back.

TEMPERATURE

Beginning in late 2007, a fourth variable was introduced: A patent pending process called Thermally Enhanced Rejuvenation (TER). TER utilizes a low voltage current source to warm the strands of the cable. As a practical matter, TER may only be applied with SPR, since imposing a warming current on an in-service cable is problematic. Warming the strands in conjunction with SPR provides three treatment benefits.

First, as illustrated in Figure 1, the viscosity of the fluid decreases with increasing temperature. From the lower viscosity alone, the flow rate would be expected to increase approximately 30% as the temperature is raised 20°C. The actual flow rate increase measured is approximately 100%. The other two less obvious benefits of TER, and the explanation for the other 70%, are an expansion of the interstitial area and much faster permeation of the rejuvenation fluid into the strand shield and the adjacent insulation. As the aluminum or copper strands expand with increasing temperature, the space between the strands grows larger too. The change in the interstitial geometry allows the injector to temporarily alter the hydraulic radius of the cable to facilitate injection. The rapid permeation of fluid into the strand shield and the insulation has the double benefit of increasing the fluid supplied to a cable during the injection period and accelerating the recovery of the cable dielectric properties.

Still another advantage of TER technology is the new ability to re-treat previously treated cables. Some utilities that rejuvenated their cables a decade or so ago with first generation injection technology are experiencing a decrease in reliability and would like to re-treat those cables to re-extend their reliable life. TER makes this possible and has been successfully practiced at a Massachusetts site.

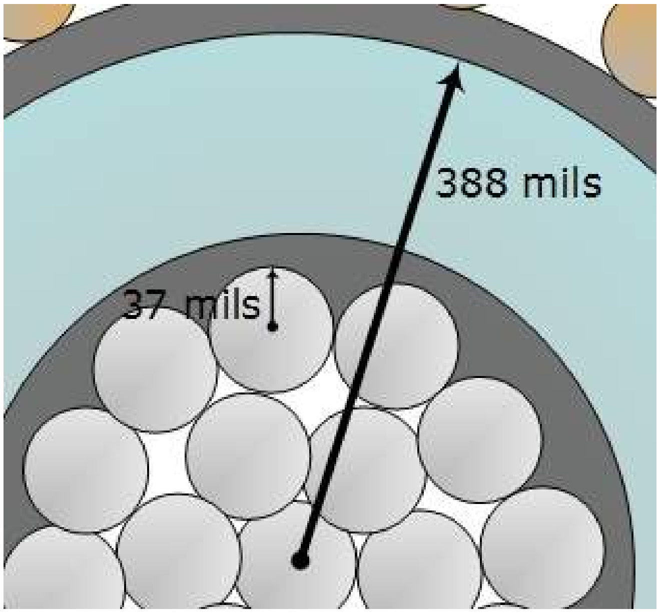

Figure 11. Cross-section of a 1/0 175 mil XLPE insulated cable demonstrates over a 9.5% (37 mils) deflection would be required to disengage the conductor shield from the conductor.

SUMMARY

Rejuvenation injection pressures up to 1000 psig have been in use for over two decades. Thousands of cables have been treated with moderate pressures in the 100 psig to 400 psig range. Every time moderate pressure injection has been examined against a lower pressure control, the higher pressure injection has outperformed the lower pressure control.

Cables are designed to accommodate the radial stresses that occur throughout their service. A cable warms with increasing load and cools when the load decreases. The 5.8-times and 6.8-times differences between the linear expansion with temperature of conductors and their insulating polymers create transient gaps between the conductor and the conductor shield. These transient gaps are a normal part of daily operation and deflections of 1% of the cable radius are common. The very similar deflection experienced when a cable is injected a single time creates no forces that are materially different and induces no geometrical deflections that are greater than a single temperature escalation from ambient to a cable's maximum operating temperature. In contrast to the daily temperature cycles endured by a cable, sustained pressure rejuvenation involves a single cycle. Because sustained pressure rejuvenation utilizes an injection adaptor with shrink-back restraint, the only possible manifestation of the single pressure cycle or future daily temperature cycles is entirely eliminated. Experiments confirm that there are no significant changes in the geometry of a cable treated with the SPR process. Field observations such as that memorialized in Figure 8 confirm the laboratory measurements.

Not only does moderate pressure injection provide higher performance (even with older technology fluids), but it also lowers the cost of injection and makes possible the use of advanced rejuvenation materials. Few circuit owners would consider buying a cable today, which did not have anti-oxidant or tree-retardant properties. The newest generation of rejuvenation fluids has about two to three times the viscosity of the first generation fluid, because these fluids include advanced functionalities that provide 2 to 4 times more post-injection life than the lower viscosity 22-year old technology.

Sustained pressure rejuvenation (SPR), thermally enhanced rejuvenation (TER), and Unsustained Pressure Rejuvenation (UPR) are tools that circuit owners should have available for their rehabilitation programs. No one tool works best in every circumstance.

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