Predicting Cable **Longevity**

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Introduction

The wire and cable industry has long sought to correlate accelerated wet aging in a laboratory with actual field performance. The industry would also like to answer the question: *What is the difference in expected cable life between materials that "just" meet industry specifications and those that outperform industry specifications?*

The following analysis attempts to address these issues by:

- Discussing two key cable testing protocols – the ICEA Accelerated Water Treeing Test and Accelerated Cable Life Test
- Comparing test results of two materials – one that meets minimum industry requirements and one that significantly exceeds them
- Extrapolating the results to help predict field performance

ICEA accelerated water treeing test performance

In North America, the industry requirements for a tree retardant crosslinked polyethylene (TR-XLPE) insulated cable are outlined in ANSI/ICEA S-94-649 clause 10.1.6, which is the accelerated water treeing test (AWTT). This testing defines the minimum AC withstand requirements for XLPE, TR-XLPE, and ethylene propylene rubber (EPR) insulated cable after wet aging (see Table 1).

With its excellent long-life performance in wet environments, TR-XLPE is the insulation of choice for most North American utilities and, therefore, will be the focus of this discussion.

Table 2 compares the ICEA requirements for TR-XLPE insulated cable and the AWTT results of cable insulated with ENDURANCE™ HFDC-4202 Insulation Compound (C4202). The data clearly shows that C4202 exceeds industry requirements, more than doubling the minimum in some cases. Using this information as a starting point, could one anticipate a difference in "real world" service life between a cable insulated with a material that performs just above the specification and a material that far exceeds the specification?

Table 2: ENDURANCE™ HFDC-4202 performance in ICEA AWTT with conventional semiconducting shields

AWTT aging (days)	ICEA requirements (volts/mil)	HFDC-4202 performance (volts/mil)*
0	660	1,320
120	660	940
180	580	830
360	380	830

*Typical values, not to be construed as specifications. Users should confirm results by their own tests.

The ICEA AWTT is conducted under very highly accelerated, wet aging conditions at a voltage stress of 3 Uo – which translates to a maximum electrical stress of 209 volts/mil (8.2 kV/mm). The test cables also undergo cyclic thermal aging at elevated operating temperatures. In the field, however, cables of the same design are typically operated (and aged):

- Under much lower stresses – field cables are operated at Uo, for a maximum electrical stress of 70 volts/mil (2.7 kV/mm)
- At much lower temperatures

Electrical insulation degradation can be modeled following an inverse power law (IPL) relationship between lifetime and electrical stress:[1]

$$E^n * t = \text{constant}$$

Where: E = electrical aging stress

n = aging parameter, typically ~ 3 for XLPE and TR-XLPE[2]

t = lifetime

The industry accepts the AWTT as a proxy for field aging, with the assumption that cable failure during field use is similar to failure during AWTT aging. It's also understood that field aging involves many unknowns (e.g., environment, installation, water content, temperature, operating conditions).

Table 1: ICEA S-94-649 minimum AC withstand values after AWTT aging

Insulation type	Minimum AC withstand values (volts/mil [kV/mm])				
	Prior to cyclic aging	After cyclic aging	After 120 days of AWTT aging	After 180 days of AWTT aging	After 360 days of AWTT aging
XLPE	620 (24.4)	620 (24.4)	300 (11.8)	Not required	Not required
TR-XLPE	629 (24.8)	660 (26.0)	660 (26.0)	580 (22.8)	380 (15.0)
EPR	500 (19.7)	500 (19.7)	420 (16.5)	340 (13.4)	340 (13.4)

Accepting these unknowns – as well as assuming the IPL applies not only for aging, but also throughout a subsequent ramp to breakdown test – the following theoretical analysis addresses our key question: *What would be the predicted difference in cable lifetime between A.) a cable with a TR-XLPE insulation that "just" meets the ICEA AWTT minimum requirements and B.) a cable insulated with C4202 that exceeds those same requirements?*

At end-of-life, based on the inverse power law,

$$E^n * t_{life} = K,$$

Where K is proportional to lifetime at a given stress, for example operating stress.

Translating an increment of aging as:

$$E^n * dt = dK$$

Where dK/K = fraction of life consumed.

In an electrical breakdown test to failure:

$$E(t) = R^*t, \text{ or t-fail} = E_b/R$$

$$\text{then } \int_0^{t-fail} [E(t)]^n dt = K$$

$$\text{or} \ldots \frac{R^n}{n+1}\left[t_{fail}{}^{(n+1)}\right] = K = \frac{1}{(n+1)R} E_b^{(n+1)}$$

Assuming material II has breakdown strength that is increased (higher) by a factor X relative to material I.

$$K_I = \frac{1}{(n+1)R} E_b^{(n+1)}$$

$$K_{II} = \frac{1}{(n+1)R} [XE_b]^{(n+1)}$$

$$\frac{K_{II}}{K_I} = X^{(n+1)}$$

Where KII/KI is the relative increase in cable lifetime at operating stress.

The data in Table 2 (previous page) shows that C4202 breakdown performance in the ICEA AWTT averages 68 percent higher than the ICEA specification requirement, which translates to X = 1.68. With an aging parameter (n) of 3, a theoretical lifetime increase of approximately 800 percent is predicted.

Such a large increase is extreme – and seems very unlikely under real world field conditions. On the other hand, it is reasonable to expect dramatically better lifetime performance from a cable insulated with material that significantly exceeds requirements, such as C4202, than one that only meets the minimum.

It should also be noted that the ICEA AWTT is conducted on short 5 m (15 ft.) cable lengths and the requirements in Table 2 are based on that length. Since cable lengths of 100 m (330 ft.) or more are typically used in the field, one must also ask: *What is the influence of cable length on the projection of cable lifetime?*

Adjusting the breakdowns in Table 2 to account for the influence of a longer cable length can be done using the following equation:[2]

$$\alpha_L = \alpha_l \, (l/L)^{1\beta}$$

Where: Eta = Weibull alpha = 209

Beta = Weibull beta = 3.82

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Table 3: ICEA requirements and ENDURANCE™ HFDC-4202 AWTT breakdowns adjusted for 100 m of cable*

AWTT aging (days)	ICEA requirements (volts/mil)	HFDC-4202 performance (volts/mil)
0	300	600
120	300	430
180	265	380
360	170	380

*Typical values, not to be construed as specifications. Users should confirm results by their own tests.

The adjustment of the 5 m test length in Table 2 to a service length of 100 m is tabulated in Table 3, with the translation yielding 55 percent of the 5 m AC withstand stress.

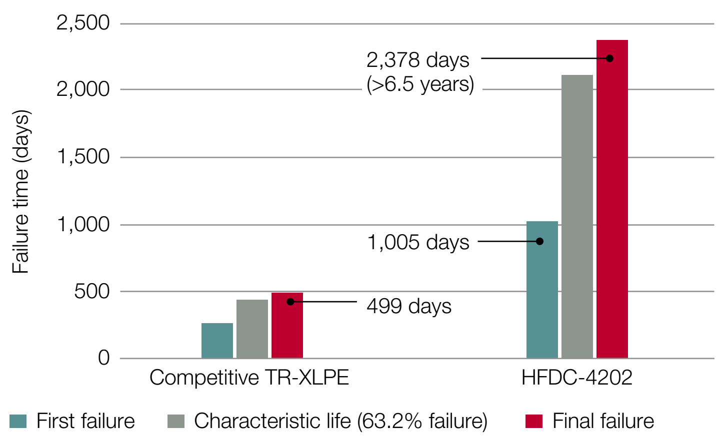
The data in Table 3 shows that a 100 m length of cable insulated with C4202 maintains a 68 percent higher breakdown than the specification requirement. As a result, a theoretical lifetime increase of approximately 800 percent is predicted once again. Thus, it is still reasonable to expect dramatically better lifetime performance from an insulated cable using C4202 compared to one that simply meets the minimum requirements.

ACLT performance

The Accelerated Cable Life Test (ACLT) is another protocol used widely in the cable industry to compare lifetime performance of cable insulations. The ACLT (IEEE 1407) is conducted under a different set of conditions than the ICEA AWTT, with multiple aging mechanisms in effect during the test. While there is no industry specification for ACLT performance, the protocol does enable head-to-head performance comparisons of cables insulated with different materials.

Figure 1 compares the ACLT performance of ENDURANCE™ HFDC-4202 to a competitive TR-XLPE that meets the ICEA AWTT requirements. The cable insulated with C4202 demonstrates a characteristic lifetime improvement of nearly five times the cable insulated with the competitive material. It is reasonable to expect a significantly better lifetime in a field application with C4202 insulated cable as well.

Figure 1: ACLT performance of ENDURANCE™ HFDC-4202 and a leading competitor*



*Typical values, not to be construed as specifications. Users should confirm results by their own tests.

Table 4: Modeling the impact of a 5 m cable ACLT performance on a 100 m cable*

5 m ACLT life (days)	Eaclt/E	100 m service life/ 100 m ACLT life	n	Expected 100 m service life (days)	Expected 100 m service life (years)
	4	80	3.16		
	4	90	3.25		
100	4	100	3.32	4,700	12.9
	4	110	3.39		
	4	120	3.45		
	4	130	3.51		
	4	140	3.56		
100	4	150	3.61	7,050	19.3

*Typical values, not to be construed as specifications. Users should confirm results by their own tests.

The ACLT utilizes cable lengths of approximately 5 m and applies a 4x rated voltage-to-ground for accelerated wet-electrical aging. The "handbook" states a range of IPL exponent values of n = 3.3 to 3.6.[1] To evaluate a service length of 100 m, we need to adjust failure expectations determined in the ACLT for length effects as well as enhanced stress. A Weibull beta value of 4 has been assumed based upon experience in failure distributions under accelerated aging conditions.

Using the appropriate length correction for 5 m to 100 m,

[(5/100)^(1/4) = 0.47],

a 100 m length under ACLT test conditions should have only 47 percent of the life of a 5 m test length.

The IPL provides a means to compare the lifetimes of a given cable length under different stress conditions.

Namely, the power law exponent,

n = ln(Service life/ACLT life)/ln(Eaclt/Eservice).

Using these assumptions of length correction and suitability of the IPL with a given value of n, we can utilize a result for aging a 5 m length under ACLT conditions to estimate the expected service life of a 100 m length under normal service conditions. (As with our discussion of the AWTT, no corrections are applied for differences in other, unknown aspects of the aging conditions, such as temperature, water content, or the presence of a protective jacket.)

Table 4 shows an analysis based on an assumed ratio of ACLT life to service life, which then defines the value of the exponent n. Next, using an assumed 5 m ACLT life of 100 days, a length correction and the life ratio provide an estimate of the expected life of the 100 m length under service conditions. Over the range of n = 3.3 to 3.6, we find that 100 days of 5 m ACLT aging translates to between 12.9 and 19.3 years of 100 m service life. It should be noted that this analysis applies for any defined B-value within a failure distribution and leads to a proportionality of lifetimes. Thus, a 5x extension of 5 m ACLT lifetime at a B10 level will translate to a 5x extension in the expected 100 m service lifetime at the same B10 level.

Overall, if a material extends the test life by a factor of X, then this analysis would suggest a proportional extension of the cable's service life.

Conclusion

Testing has shown that cables made with ENDURANCE™ HFDC-4202 Insulation Compound exceed the industry minimum AWTT requirements and significantly exceed the ACLT performance of other competitive materials. Based on the findings presented in this paper, one can conclude that proper use of ENDURANCE™ materials from Dow supports expectations of significantly longer cable service life.

References

[1] H. Orton and R. Hartlein, *Long-life XLPE-insulated Power Cables*, Chapter 4.6.2 (2006).
[2] N. Hampton, J. Perkel, and T. Parker, *Bridging the gap between Lab Tests and estimates of Service Performance* (Spring 2017 ICC A6D Meeting).

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