ICEA Standard S-97-682 Hyperbaric Accelerated Water Treeing Test (AWTT) Performed at 1, 250 and 310 bar

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ABSTRACT

The Accelerated Water Treeing Test (AWTT) of ICEA standard S-97-682 has been performed on tree-retardant crosslinked polyethylene (TRXLPE) insulated cables having blocked and unblocked conductor strands, at 1 (ambient), 250 and 310 bar hydrostatic water pressure for up to 450 days. Minimum residual dielectric AC breakdown strength requirements of the ICEA standard after AWTT via a step-rise high voltage time test (HVTT) at 120, 180 and 360 days were met at all three (3) test pressures, and were statistically equivalent at all test pressures. Degradation rates of AC breakdown strength were also identical at all test pressures. The number of bow-tie trees observed at or near HVTT failure sites as a result of AWTT being performed at 250 and 310 bars were higher than at ambient pressure (1 bar). The bow-tie tree density (#/.in3) growth rates at 250 and 310 bar are also greater than at 1 bar. Vented treeing (either at the conductor shield or insulation shield interfaces) at 250 and 310 bar was essentially non-existent. These test results indicate that this TRXLPE insulation system can be expected to operate reliably at its intended operating voltage in sea water depths of up to 10,000 feet (3,100 m) for its projected 30 - 40 years life.

KEYWORDS

Accelerated Water Treeing Test, AWTT, AC breakdown strength, bow-tie trees, vented trees, hyperbaric pressure, TRXLPE, degradation rates, high voltage time test, HVTT, submarine cable

INTRODUCTION

The oil and gas industry is moving into ever increasing water depths in the search for new oil and gas supplies. Subsea developments and operators are looking towards subsea boosting technology as a means of getting the most out of their reservoirs. The power distribution cables and umbilicals, which are needed to supply electrical power to the subsea boosting equipment, will be challenged by more extreme conditions due to the deeper waters.

The incremental increase in production from pumps installed on the seabed or in the well, and / or compressors installed on the seabed can be the determining factor in the economic viability of a deep or ultra-deep water production field. When power is supplied from floating structures in deep waters, dynamic cables and multi-function umbilicals are required to supply power to the subsea electrical loads. In addition to one or more medium or high voltage three phase power circuits, the umbilicals may include fibre optic communication cores, control power conductors, and tubes for barrier, control, or other fluids. The dynamic submarine cables and dynamic umbilicals material and installation costs represent a significant portion of the subsea boosting cost.

Because of the significant costs, and frequently the limits in number of hang offs from floating structures, these cables are often un-spared, and are critical components of the production system. A single subsea load may supply the equivalent of 60,000 barrels a day. Production fields and facilities may have expected life of 25 to 30 years or more. In order to achieve the required reliability and availability throughout the life of the fields, it is imperative that all measures are taken to ensure proper design, manufacturing, testing, and installation of the submarine cables and umbilicals.

The installation of power cables in deep waters involves comprehensive engineering studies which analyse all critical installation aspects including interaction of mechanical, electrical and thermal properties between the power cables and umbilical or other installation components. Generally, this type of cable and umbilical installations will involve dynamic sections and static sections. Among other types of specific constraints (e.g. mechanical stresses –fatigue, tensile loads, creep, etc.) which will significantly influence the power cable designs and the qualification testing definition [1], high hydrostatic pressure is an important factor to take into account to fully evaluate the cable design and materials to be used.

For cables with wet design (without a metallic barrier to stop the radial diffusion of water into the insulation), it is of major importance to evaluate the water ageing behaviour of the cable insulation system (conductor shield, insulation, insulation shield materials and the cleanliness of the manufacturing process). The water-treeing degradation behaviour for land-based cables is well addressed via the Accelerated Water Treeing Test (AWTT) protocol stated in North American and International standards such as ICEA S-97-682 [2], Cenelec HD 620 [3] and Cenelec HD 605 [4].

Since these standards do not provide accelerated degradation conditions for hyperbaric applications and specific submarine cable design particularities [5], the present study has been carried out to gain knowledge of the influence of high pressure on the water ageing process. The intent is to compare the ageing behaviour (degradation of AC breakdown strength and water-tree growth rates) of different cable core designs (blocked and unblocked stranded conductor) at different pressures (1, 250 and 310 bar). The test procedures that were used comply with ICEA Standard S-97-682, Part 10 and AEIC Cable Specification 8, Section 15. AC breakdown strength results are compared with the pass / fail criteria of S-97-682. Since ICEA S-97-682 nor AEIC CS8 contain no minimum treeing performance requirement, treeing results at hyperbaric pressures are compared to those obtained at atmospheric pressure (1 bar), and to those of a non-tree retardant XLPE insulation.

TEST PROTOCOL

Test specimens

All tests were performed on cable designs as stated in ICEA S-97-682 Part 10 (1/0 AWG with compressed class B stranding, 15kV at 100% insulation level of 4.5mm insulation thickness).

The identities of the materials used are coded to maintain anonymity. However, extruded semiconductive shielding materials (conductor and core screen) were the same for all cable designs and were not of the superclean acetylene carbon black and/or the supersmooth type, but were of the conventional type. Cables were produced in a manufacturing site with machinery commonly used for commercial production of submarine cables using true-triple extrusion and a dry-cure continuous vulcanization process. All cables were subjected to the required ICEA S-97-682 factory acceptance testing before being subjected to the testing described in this paper.

Based on the described overall design and manufacturing process, two types of designs were tested:

- Without any water blocking compound inside the conductor strands (as stated in the ICEA S-97-682 Standard); named as unblocked cable.
- With water blocking compound inside the conductor strands; named as blocked cable. The method of blocking the conductor consisted of applying a commercially-available pumpable mastic compound into the conductor strand interstices during manufacture of the stranded conductor.

For the proper comparison and statistical analysis of voltage strength breakdown data, all samples' active length used in the High Voltage Time Test (HVTT) was 22 ± 3.3 ft (6.71 ± 1m).

Test procedure

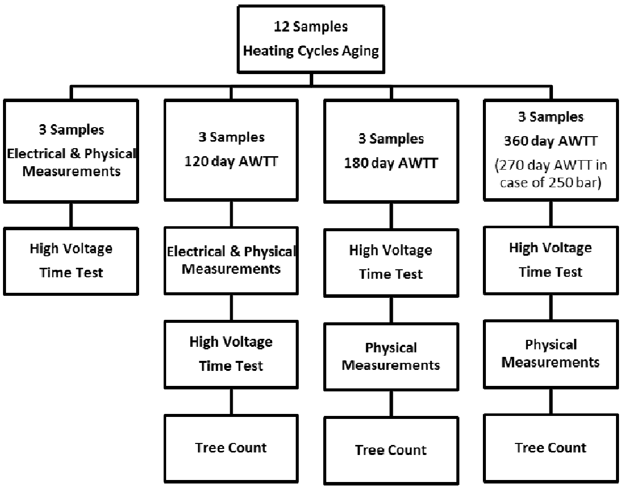

Fig. 1: Testing protocol flow chart

The AWTT was performed based on the ICEA S-97-682 Standard Part 10 procedure, adapted to the following three different pressure levels:

- 1 bar (as stated in the ICEA S-97-682 Standard)
- 250 bar; simulating approximately 8,000 feet (2,500m) water depth
- 310 bar; simulating approximately 10,000 feet (3,100 m) water depth

The blocked cable was aged at the three different levels of pressure while the unblocked cable was only aged at 1 and 250 bar. This resulted in five different testing processes, each one following the protocol and flowchart summarized in Figure 1.

Cyclic Aging

Cyclic aging is conducted to remove the majority (>99.95wt.%) of the volatile crosslinking by-products found in freshly manufactured cable [2]. The cable was subjected to 14 current cycles of 8 hours on and 16 hours off, at a sufficient amperage level to achieve a conductor temperature of 130°C +0/-5°C during the last 4 hours of each 8-hour on period of heating.

Electrical and Physical Measurements

Dissipation factor, capacitance, partial discharge, conductor shield thickness, insulation thickness and insulation shield thickness were measured for all samples at different steps of the testing protocol.

AWTT

A voltage of 26 kV AC was applied and maintained for the entire test period. Simultaneously, temperature was applied on the cables, for 8 hours on and 16 hours off, 5 days a week, achieving 45°C ± 3°C on the cable insulation shield surface in the water within the last hour of the 8-hour on period. Sets of 3 samples were taken out of the water tank after 120, 180 and 360 days of ageing and immediately subjected to AC breakdown testing via the HVTT. The samples aged at 250 bar were only aged to 270 days instead of 360 days.

Different water reservoirs were used at different General Cable laboratories. AWTT at atmospheric (1 bar) pressure was performed in open-ended PVC pipes, while AWTT at hyperbaric conditions (250 and 310 bar) was done in the pressure vessel shown in Figure 2.

Fig. 2: Pressure vessel used for hyperbaric ageing at General Cable Manlleu Testing Laboratory

High Voltage Time Test (HVTT)

The purpose of this test is to measure the initial and residual (before and after) AC voltage breakdown strength of the cable by raising the applied voltage in a constant step duration-stress profile. A test voltage equal to 100V/mil (3.9kV/mm), based on the nominal insulation thickness of 4.45mm (17.4 kV), was applied and held for a period of 5 minutes. The voltage was then increased in 40 V/mil (1.6 kV/mm) steps (7.12 kV/step), and held for 5 minutes at each value, continuing to cable breakdown [2].

Tree Count Test

Upon completion of the HVTT's conducted on three samples for each AWTT aging period, 10 wafers approximately 25 mils (0.64 mm) thick were cut from each of the three cable breakdown sites, which included the wafer containing the actual breakdown site location. The resulting 30 wafers were dyed in an appropriate manner and examined for water and electrical treeing under 40X magnification [5]. Calculations of tree densities (#/in^3) were made for all three category types; Bow-Tie, Vented and Electrical and size ranges.

Data Analysis

The Weibull Distribution is the most widely used statistical model for dielectric insulation breakdown data analysis. The equation for the 2-parameter (2-*p*) Weibull cumulative distribution function is given by:

$$P_f = 1 - e^{-\left(\frac{x}{\eta}\right)\beta} \qquad [1]$$

Where P_f is the cumulative probability of failure, x is the random variable (breakdown voltage), ETA (η) is characteristic value/life, BETA (β) is the slope/shape parameter and *e* is the base of natural logarithms. Hypothesis testing of population's results was also utilized to determine statistically significant differences or equivalency [6], [7] between aging periods, test pressures and cable designs.

RESULTS

The data obtained after AWTT at 120, 180 and 360 days (270 days for the 250 bar aged samples) in this study was the following for each of the three test pressures and the two cable designs:

- Residual dielectric AC breakdown strength via (HVTT); results summarized in figures 3 to 7 below.
- Tree count observations and calculations; results summarized in Table 1 below.

Cyclic ageing and all electrical and physical measurements were performed in accordance with ICEA Standard S-97-682 Part 10 methodology. All results of all samples met the minimum requirements of the Standard.

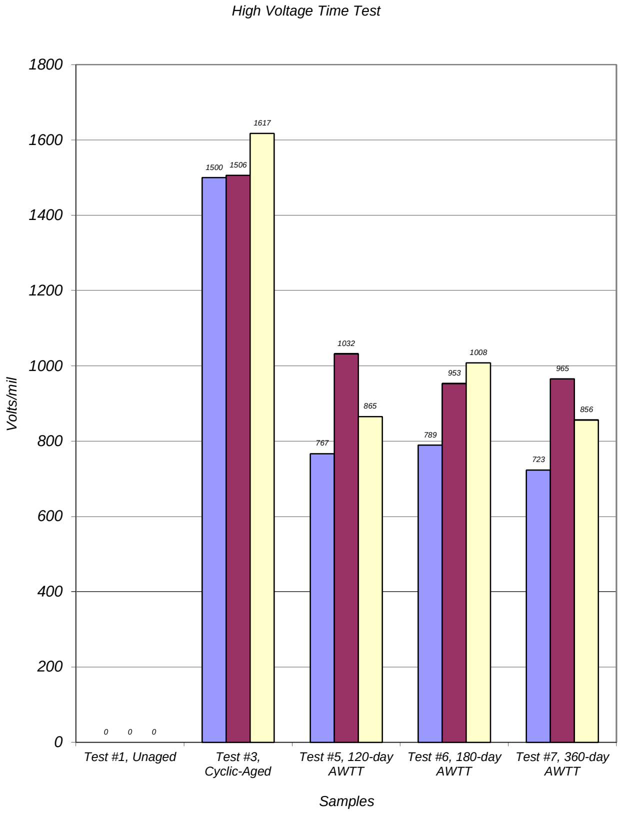

Fig. 3: Unblocked cable AC breakdown strength after AWTT at Atmospheric (1 bar) pressure

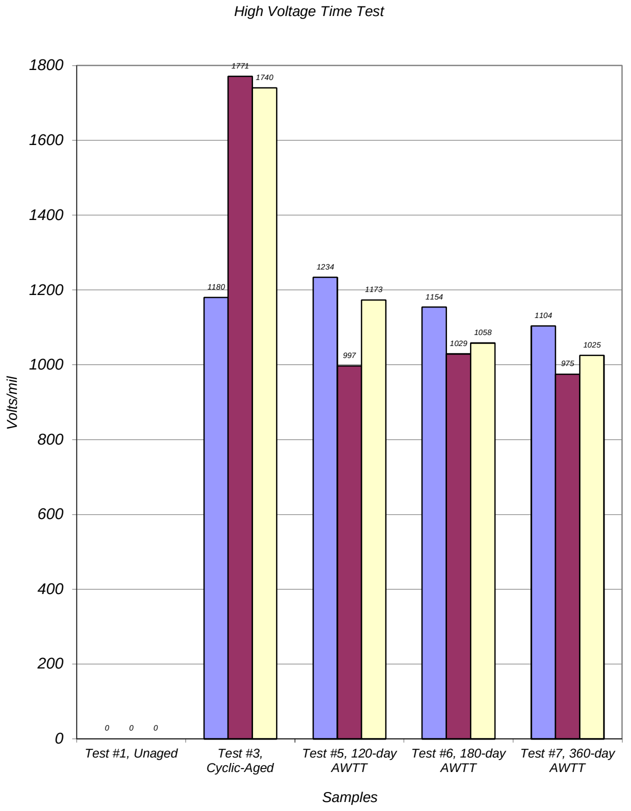

Fig. 4: Blocked cable AC breakdown strength after AWTT at Atmospheric (1 bar) pressure

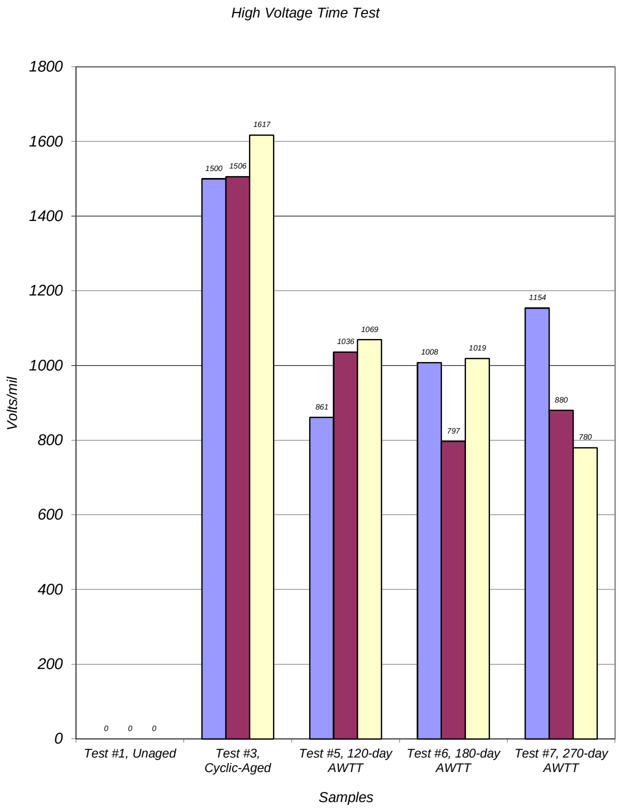

Fig. 5: Unblocked cable AC breakdown strength after AWTT at Hyperbaric (250 bar) pressure

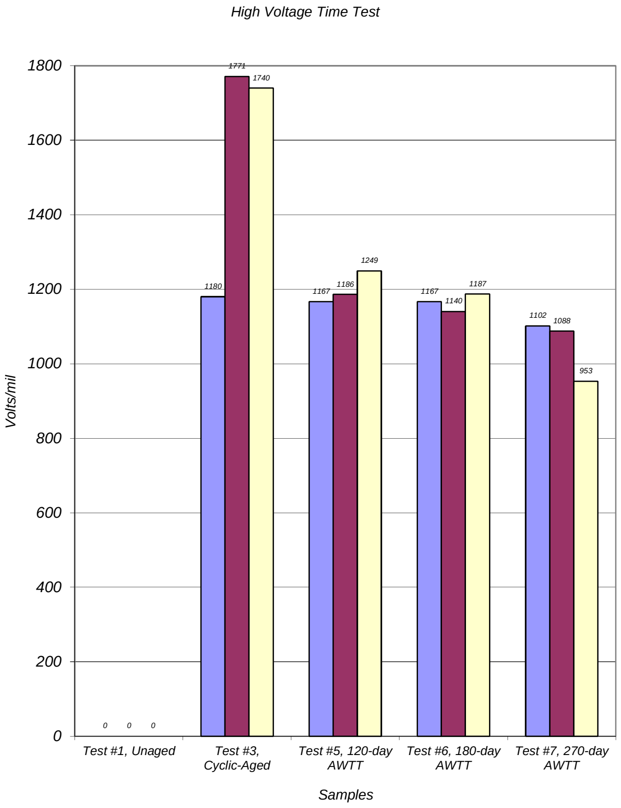

Fig. 6: Blocked cable AC breakdown strength after AWTT at Hyperbaric (250 bar) pressure

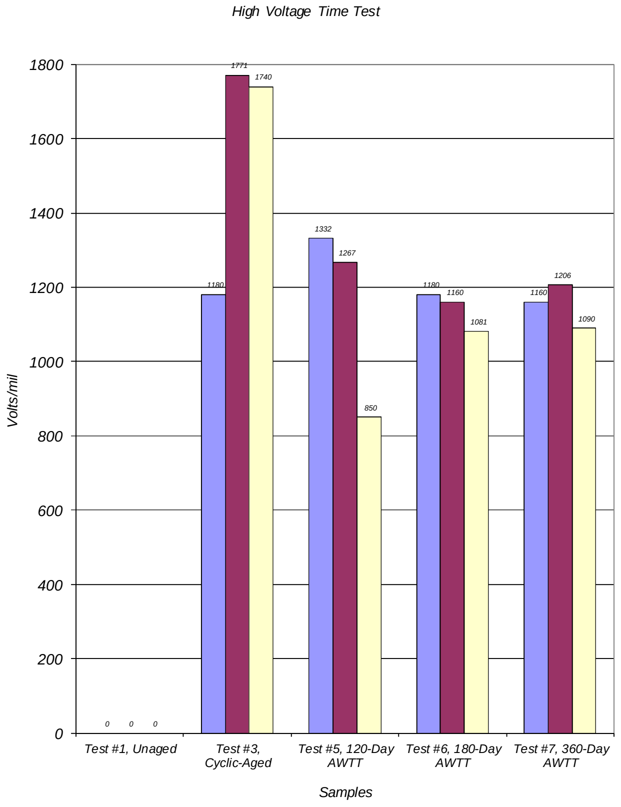

Fig. 7: Blocked cable AC breakdown strength after AWTT at Hyperbaric (310 bar) pressure

Tab. 1: Tree density calculated for each cable design, AWTT pressure and ageing time

Pressure Cable design	Tree size (mils)^{2,3}	Bow-tie Tree Density (No./in^3)		
		After 120 days	After 180 days	After 360^1 days
1 bar Unblocked	6 - 10	0	35	123
	11 - 20	0	0	0
1 bar Blocked	6 - 10	0	23	11
	11 - 20	0	0	7
250 bar Unblocked	6 - 10	102	120	108
	11 - 20	0	0	0
250 bar Blocked	6 - 10	11	23	23
	11 - 20	0	0	0
310 bar Blocked	6 - 10	23	38	85
	11 - 20	0	0	0

[1] ***270 days in the case of samples aged at 250 bar***

[2] ***No bow-tie trees >20 mils observed***

[3] ***No vented or electrical trees observed***

Evaluation criteria

The intent of this proposed test program is the evaluation of the results of each test against the following criteria:

1. ICEA S-97-682-2007 (Table 10-1) minimum withstand stress requirements criteria for **each** sample:

	Minimum AC Withstand Values, V/mil (kV/mm)			
Insulation Type	**After cyclic aging**	**After 120 Days of AWTT aging**	**After 180 Days of AWTT aging**	**After 360 Days of AWTT aging**
Tree Retardant XLPE	**660 (26)**	**660 (26)**	**580 (22.8)**	**380 (15)**

2. Mean of AC breakdown stress (as determined via statistical analysis of the breakdown stress results using the 2-parameter Weibull distribution) vs. AWTT aging time and test pressure
3. Degradation rates of mean AC breakdown stress
4. Assessment of the effect of hyperbaric testing on water-treeing and its subsequent effect on residual AC breakdown strength.

DISCUSSION

Criterion 1

The ICEA minimum AC withstand requirements are intended to demonstrate that materials and cable designs meeting these requirements and installed in wet environments are fit for reliable long-life service. HVTT results (Figs. 3 – 7) of the five (5) AWTT combinations of pressure and cable design show that each test sample met and exceeded the minimum AC withstand requirements of ICEA standard S-97-682 by factors of 2 - 4 times for each ageing period and each test pressure.

Criterion 2

Statistical analysis of the data sets using the 2-p Weibull distribution indicate that the mean withstand values (η) of the hyperbaric AWTT are somewhat surprising. (See Fig. 8) Comparison of the mean withstand values (and their 90% double-sided confidence bounds) of unblocked cables at 1 bar and 250 bar, show 250 bar results to be superior or statistically equivalent to 1 bar results through 180 days AWTT.

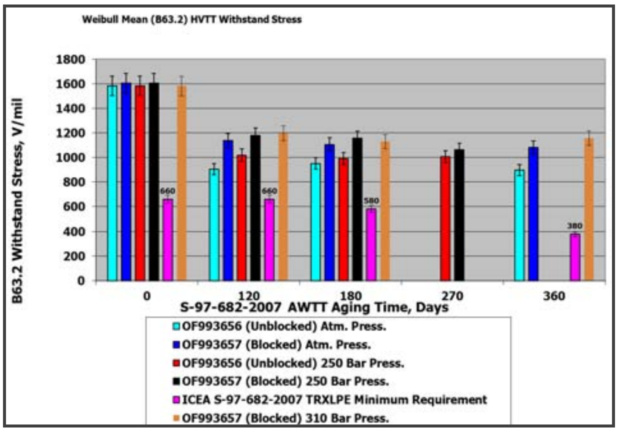

Fig. 8: Weibull mean HVTT withstand stress for each cable design, AWTT pressure and ageing time

However, power cable designs for deep sea applications (blocked conductor strands) are of more interest. Although AWTT at 250 bar was stopped for unblocked and blocked cables at 270 days, extrapolation to 360 days predicts the same result. Comparison of the mean withstand results for blocked cables vs. unblocked cables show blocked cables to be numerically higher, and statistically equivalent to unblocked cables. Results also show that 250 and 310 bar mean values are also numerically higher, and statistically equivalent to the atmospheric (1 bar) result.

Criterion 3

The summary of residual AC breakdown strength degradation rates is shown in Table 2.

Tab. 2: AC breakdown strength for each cable design and AWTT pressures

Exponential Regression Fit of AC Withstand vs. AWTT Ageing Time						
$Y = A*e^{(nX)}$						
Cable Design/ Test Pressure	**A**	**n**	**X, Ageing Time @26kV, Days**	**$e^{(nX)}$**	**Y, Operating Stress @ X, V/mil**	**Estimated Performance Rank**
Blocked/310 bar	1510	-0.0008	4218	0.03424	49	1
Blocked/250 bar	1530	-0.0010	3442	0.03203	49	2
Blocked/1 bar	1432	-0.0010	3375	0.03423	49	3
Non-Tree Retardant (Unblocked) GCC Results/1 bar	1139	-0.0030	1050	0.04285	49	4
Unblocked/250 bar	1583	-0.0037	940	0.03087	49	5

Calculated degradation rates of residual AC withstand strength of blocked cable is inversely proportional to pressure, with the slowest rate observed at 310 bar. This is a surprising result, in that radial hyperbaric hydrostatic pressures might be expected to impart increased water levels in the cable insulation, leading to increased water-treeing rates, resulting in faster degradation rates of residual dielectric strength. It is well understood that bow-trees in XLPE insulation leads to reductions in AC breakdown strength. While it is observed in Table 1 that bow-trees are increased at hyperbaric pressures, their effect on residual AC dielectric strength is not observed. This result might be explained by increased mechanical forces (compression) exerted on the insulation system in an elevated temperature condition, suppressing microvoid formation and water-tree growth to lengths that would result in lowered breakdown strength. Table 2 predicts aging time (days) for dielectric strength to drop to the operating voltage of the 15kV-rated cable design at hyperbaric pressures, based on testing at 3X operating stress. If the inverse power law model of ageing is operable as is shown for this insulation type (TRXLPE) in [6], then this blocked cable design at 250 and 310 bar could be conservatively expected to remain reliably operational for a 30 – 40 year timeframe.

Criterion 4

The treeing results of the hyperbaric AWTT are somewhat surprising. The AC breakdown strength results of these cables (Fig. 8) do not appear to be affected by the observed treeing performance (Table 1). In addition, there appears to be excessively high small bow-tie treeing observations in the unblocked cable at 250 bar. AWTT of unblocked cable was not performed at 310 bar.

However, tree density projections at 310 bar, based on AWTT at 1 and 250 bar for unblocked cable, indicate unblocked cable results at 310 would be less than those observed at 250 bar. Investigation of this unexpected treeing result at 250 bar showed that during the commissioning/check-out of the hyperbaric ageing tank containing the unblocked and blocked cables for 250 bar testing, a rapid de-pressurization of the tank from 250 bar to atmospheric (1 bar) pressure occurred on at least one occasion. Since water was not injected into the unblocked cable's conductor interstices during this commissioning/check-out of the operation of the vessel, this might explain the contradictory treeing results observed at 250 bar AWTT. With the conductor interstices of the unblocked cable length sealed between the 2 sealing glands and containing compressed atmospheric air (not water) during this commissioning/check-out, a quick de-pressurization of the water-filled vessel would necessarily cause voids to be formed in the insulation bulk as the air in the conductor interstices de-compressed during de-pressurization of the vessel. This rapid de-pressurization of the cable insulation would have occurred at elevated temperatures (45°C ± 3°C on the cable insulation shield surface in the water) with a temperature difference of zero across the insulation cable core thickness, and with the cable core containing dissolved air (oxygen, nitrogen, carbon dioxide). The cable under these conditions is analogous to a deep sea diver experiencing the "bends" when being brought to the surface too quickly. If equalization of the dissolved gas pressures (nitrogen, carbon dioxide, carbon monoxide) in the blood/cable insulation is not allowed to take place slowly, gas bubbles (voids) form in the blood/cable insulation, resulting in large concentrations of microvoids. It is suspected this phenomenon is what lead to the observation of high bow-tie tree counts and densities for the 250 bar AWTT in the 6 – 10 mils size range.

CONCLUSIONS

The TRXLPE insulation system and blocked conductor design used in this testing are capable of providing residual AC dielectric breakdown strength performance at hyperbaric pressures (2 – 310 bar) that is equivalent to (and in some cases superior to) performance at atmospheric (1 bar) pressures. While treeing densities increase as a function of increasing pressure and ageing time, residual AC breakdown strength remains high and is not a function of increasing pressure or treeing densities; it remains a function of ageing time only.

These results indicate that this insulation (TRXLPE) system and cable design (blocked conductor) are suitable for deep sea submarine and umbilical applications. Other TRXLPE insulations and different designs of blocked conductor (water-swellable powders and/or yarns) should be tested to verify that they are suitable for hyperbaric applications in wet environments. Since the ICEA standard wet-ageing protocol and minimum withstand requirements used in this study infer reliable, long-life operation of land-based cables that meet these requirements, and since these results at hyperbaric pressures are equivalent to atmospheric results, it can be inferred from these results that the TRXLPE blocked cable design used in this study will have similar reliable long-life service in deep sea applications.

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