WILL YOUR CABLE REALLY LAST 8.10^8 SECONDS?

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Abstract: High voltage capability of repeated submarine systems to ensure adequate power feeding to the repeaters is fundamental for long term reliability. A deeper knowledge of cable electrical reliability is more and more critical and leads to a finer control of cable electrical performance. To demonstrate this high reliability, an adequate and thorough qualification protocol is essential. Protocols have been thoroughly investigated and reinforced to push cables and joints to their limits and get more out of the product performance and capability. The investigation and interpretation of results have been validated by an independent expert.

This paper describes the new qualification regime and reports results obtained during an extensive evaluation program conducted on different Alcatel-Lucent Submarine Networks cables.

1. INTRODUCTION

Long term testing and long term ageing are of a paramount importance in a wide range of industries to establish reliability: cosmetics, electronics, food… and also in the submarine cable industry where repair costs are extremely high, making product reliability extremely important. By putting a product under stress above its normal service level, failure modes and service life reliability can be determined.

2. BACKGROUND

Industry standards

One approach is to put pieces of cable in their service environment (voltage, immersion in sea water, etc) for 25 years and see what happens; but this approach is not particularly efficient and needs several generations of technical people to pass on the baton! Another option would be to stress the cable at a specifically chosen, higher, but still moderate voltage, for a certain time. In the telecommunication cable industry several well-known protocols are used based on such industry "rules of thumb" - screening the product and its manufacturing process or attempting to simulate its ageing. The associated and simplified qualification process uses simple test plans in which a small number of cables, which could even come from the same extruded length, are tested at a voltage which is higher than the service voltage for a given time.

Products qualification

As far as qualification tests are concerned, the most common process encountered in our industry is to apply a higher voltage for a period of time to simulate the in-service system lifetime based on a simplified form of the "inverse power law", derived from the "usual" statistical reliability model:
$t = kV^{-n}$
where k is a constant, t is the time to failure at a given electric field V and n is the Life Exponent, the "n-factor".
As a practical example a cable to be qualified for a 25 years' service life at a system voltage of 12kV would be tested at 160kV for one hour, assuming a value of 4.75 for the "n-factor". This "n-factor" is

determined from experimentation and various, more or less conservative considerations, sometimes derived using a statistical analysis of the test results.
The applied voltages vary from place to place (i.e. from one supplier to another), being dictated by various industrial considerations (such as personnel safety, availability of DC testing equipment, constraints associated to the environment…) as well as the practical considerations of the time during which the voltage is to be applied; a test lasting several months being a significant burden as far as available test equipment is concerned.
Several further aspects are to be kept in mind in this kind of qualification/type test, such as the length and the how representative of the population are the samples under test, as well as the unwanted side effects of applying a voltage level far higher than the one that will be applied in service which might generate non representative failure modes. To mitigate this latter issue, an additional qualification test protocol consisting of the application of a moderate voltage (typically 45kV) for a duration of several months, or other combinations of higher voltages/longer durations, have also been used. Of course all these tests are "destructive" and they are considered to correspond to the product lifetime. Polarity is also reversed during the 45kV qualification test in order to simulate service operations in the event of a repair.

Product screening

Qualification is a first step but all cables also need to be screened to guarantee the service lifetime reliability.
As far as screening is concerned one can note the "usual" +/-45kV applied for 5 minutes, frequently listed as a requirement in technical tendering specifications and used to eliminate "big" flaws in the cable insulation layer. Of course to maximize the efficiency of such a test it has to be made on the LW cable immersed in water over its entire length.

3. STATISTICAL APPROACH

A complete and rigorous approach is to conduct a full blown statistical analysis in order to model and predict the product performance in long term aging. As is usual with structural failure modes (e.g. crack growth) such analysis is conducted through a series of ramp-to-failure tests and stress-to-failure tests. Such an approach requires a lot of work and is long (in particular long term stress testing) but it is essential in order to evaluate the reliability of what is being offered: particularly when introducing a new technology or in situations where it is necessary to have evaluated the existing margins between product ultimate performance and its conditions of use.
By adopting a statistical approach this paper takes further the approach presented above in order to have a real working knowledge of the variability within the system.
To do long term testing on several samples from one cable is not representative so we made the decision to take a significant number of cables, insulation lines, speeds, cable types, copper conductor substrates, batches of polyethylene etc. and this over a period of several years giving a total number of samples tested of over 600. Each of the above parameters can have a significant effect on the variability of the electrical performance of the cable and joints. For example, cable process parameters (extrusion speed, temperature profile, tooling etc …) can all have an

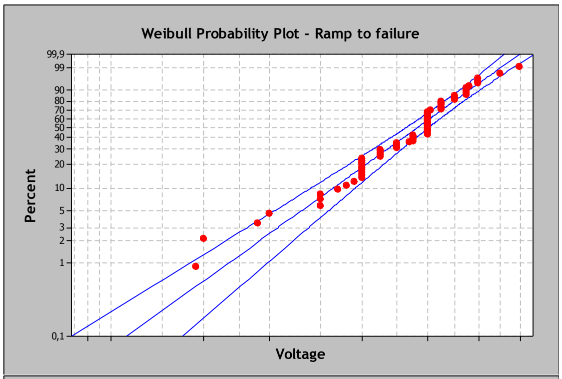
effect on cooling and the cristallinity of the polyethylene. Testing several copper substrates and batches of polyethylene gives an idea of the natural variability of materials and their effect on the electrical performances of the products.
This series of testing, over several years, has helped us establish a rigorous protocol to guarantee system reliability over the required 8.10^{8} seconds (25 years)., with a high level of confidence.

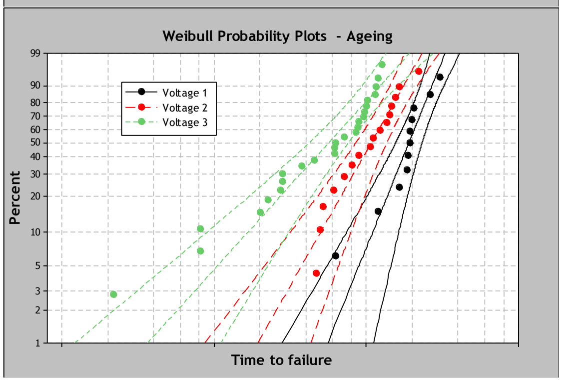
Testing equipment and testing protocol

Of course all this does not go without adequate testing equipment. Alcatel Lucent Submarine Networks uses a range of 8 different DC ageing platforms ranging from 50kV up to 400kV.
Safety is key in the potentially dangerous conditions of electrical testing. Operators are fully qualified and certified, and fully equipped with the necessary safety equipment; the test rigs are all contained inside a Faraday cage. The electrical generator and the cage door are interlocked; if the cage is opened, the voltage is automatically switched off. Cable connections are made using bus-bars.
Two types of testing have been done: one is ramp-to-failure testing, the other one ageing at different voltages both followed by a Weibull analysis of the breakdown data. Using the results of these points and coupled with a forensic investigation of breakdown sites, a model has been established and the reliability of the cable can be guaranteed. Several levels of ageing are necessary in order to be able to calculate the n-factor with as much accuracy as possible. The n-factor is derived directly from the slope of these points. Using the comparison between this slope and the target of 25 years service lifetime, we can confidently evaluate the margin.

These points are derived from the characteristics of the Weibull plots (63% probability).
This approach is used for cable and also for cable joints and both are taken into account in the final calculation of the n-factor.
Taking an example; cable samples from different origins have been tested:

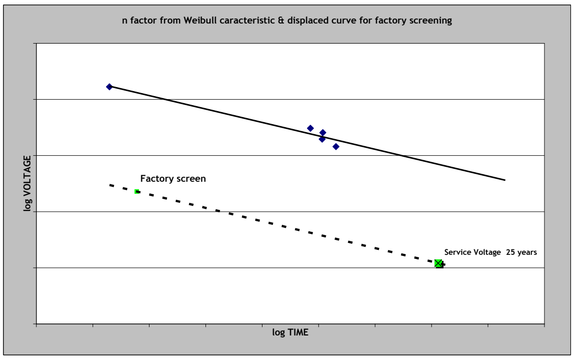
- Up to ramp-to-failure, using a standardized voltage increase and stabilization, which gives a Weibull distribution of breakdown voltages.
- Ageing at 190kV
- Ageing at 160kV
- Ageing at 140kV
- Ageing at 120kV
- Ageing at a voltage close to 50kV so as to be nearer to the service voltage and with a reversal of polarity





Screen test level setting

Analysis and testing do not stop here as variability is part of day-to-day life. It is important that any possible latent defects are removed at the factory before any cable is even shipped. Here again a range of “screen-tests” is used within the submarine cable industry (on cables and joints). An appropriate screen-test has to be defined to remove any tail of the distribution from the lengths of cables that could possibly fail on ageing over several years. The level of test has been calculated using the n-factor derived from the extensive testing protocol. As shown below, we have translated the n-factor line towards the system lifetime (25 years) in order to obtain equivalent levels of screen-test which will remove any latent defect and to be in a confident position to be able to guarantee the system lifetime.

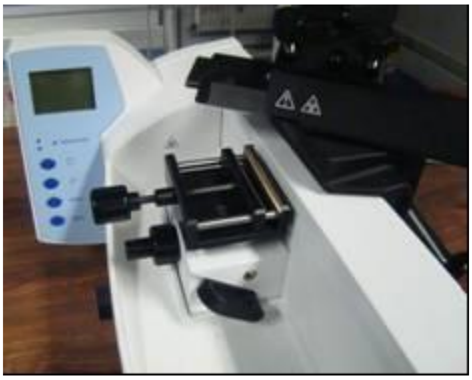


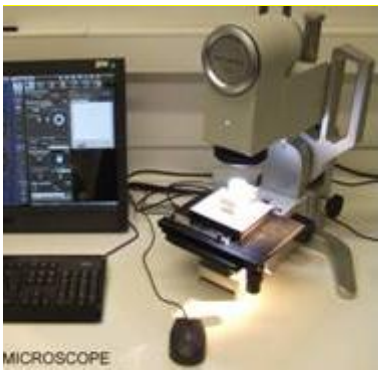
4. FAILURE SITES ANALYSIS

But here again this is still not enough. It is not sufficient to rely only on test data and mathematical analysis; all breakdown sites must be thoroughly inspected in order to identify the root causes of the breakdowns. To be able to carry out such in depth analysis, a wide range of highly specialized equipment needs to be and has been used:

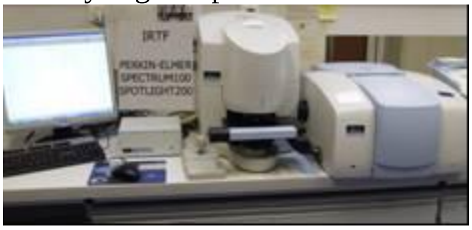
- Digital X-Ray to detect metallic particles in the insulation layer

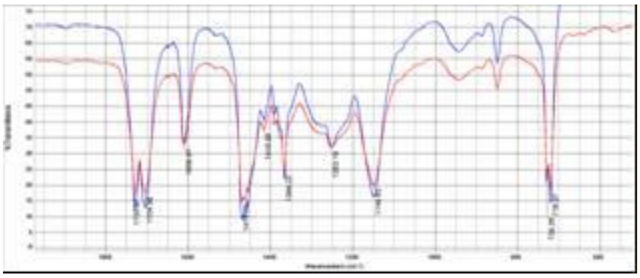
- Microtomes to prepare fine slices of polyethylene that are examined under the microscope using polarized light to detect residual constraints



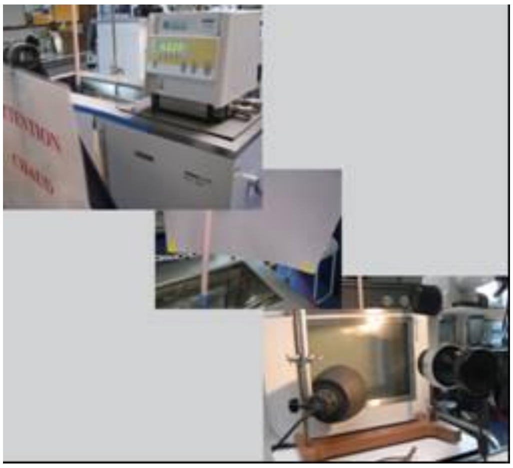


- The same fine slices are analysed using FTIR (Fourier Transform Infra-Red Spectroscopy) to detect any organic pollution

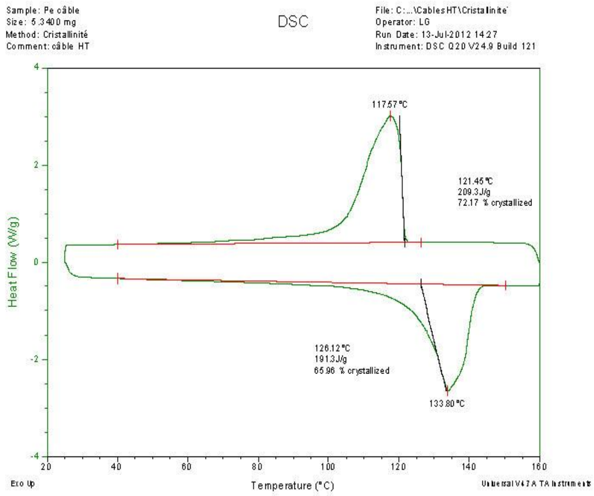




- A custom-built hot-oil bath method has been developed to reveal electrical treeing and locate the source of the breakdown



- DSC to measure the cristallinity of the polyethylene, its Oxidative Induction Time (OIT) and any organic contamination



- UltraPycnometer to measure density

- Inspection of cable cross-sections using a high-resolution, digitized computer-controlled profile projector to measure thicknesses and to check cable concentricity

- Linear shrinkage of cable or joints to determine the level of residual constraints

These inspections have allowed a better understanding of these phenomena, helped to build the model and opening up new and rewarding paths for continual improvement.

5. CONCLUSION

Through an extensive testing program based on more than 600 tests, ramp-to - failure, ageing at different voltages and forensic examination of breakdown sites, Alcatel-Lucent Submarine Networks has developed and implemented a qualification regime that allows, with a high level of confidence, a better estimation of the system electrical margin.