IMPROVED UNDERSTANDING OF EXTRUDED MV CABLE PERFORMANCE THROUGH THE MODIFICATION OF EXISTING APPROVAL PROTOCOLS

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ABSTRACT

Cable users and manufacturers have an increasing wish to gain a deeper understanding of cable performance, beyond the knowledge that it simply complies with the minimum performance level defined within a standard. Although approval test protocols have served this purpose well, they do not provide the level of sophistication that is required for a detailed analysis. This paper describes many of the common shortfalls in current test protocols and advocates a number of simple modifications to procedures. These modifications will make approval test methods better able to address the more detailed discrimination being requested today.

KEYWORDS

TESTING, MEDIUM VOLTAGE, AGEING

INTRODUCTION

Cable users and cable manufacturers have derived significant benefit in system reliability from improved medium voltage (MV) cable quality. One of the important elements in this improvement has been the widespread use of recognised qualification tests such as those outlined in CENELEC HD605, ICEA S-94-649 and IEEE 1407 [1,2,3]. These tests generally have well defined ageing and evaluation procedures. The associated "success criteria", such as those defined in CENELEC HD605 and ICEA S-94-649, serve to discriminate and assure that cable users can be certain of minimum levels of cable performance.

However, users are now wishing to understand more about the cables they use and they find that these essentially pass / fail tests do not fully satisfy this need. The criteria and methods in these tests are designed to show differences between proposed designs and those that have historically performed poorly rather than determine an absolute performance level [4]. Thus it is difficult to use these standard tests to address issues that were not within their original scope. This paper describes a number of test programmes that extended, or upgraded, the "normal" protocols to derive a better understanding of cable performance.

The test programmes described include:
a) a five year study of the endurance performance of complete cable designs conducted in large tanks
b) an evaluation of cables of different voltage classes
c) an evaluation of cables after ageing in long tubes for twice the normal period.

These projects have highlighted a number of interesting points which are discussed in greater detail within the paper. Most of the comments reported here are directed toward tests which involve ageing over time followed by a final breakdown assessment.

ACHIEVING A 'TRUE' CABLE BREAKDOWN

Early cable systems tended to have low breakdown strengths [4], especially after aging. Thus it was relatively straightforward to achieve true cable breakdowns (punctures of the dielectric within the active length – central portion of Figure 1) and produce a dataset essentially free of termination failure and flashovers. However, improvements in the quality of cable has led to an increase in dielectric strength. This leads to the increased likelihood of test termination failures and flashovers (Figure 2). In addition, some HV test sets now have insufficient voltage to cause failure. These features are commonly referred to as "censored data" or "suspensions" [5 - 8]; which can most conveniently be thought of as failures that have occurred but not by the mechanism under study. The increasing proportion of these censored data reduces the number of valid data points available for analysis. The larger the number of true failures, the clearer and more significant the test conclusions will be.

Figure 1 MV cables undergoing ac breakdown testing after long term wet ageing

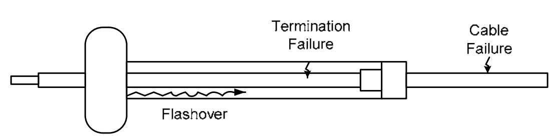

Figure 2 Types of test results – schematic showing the types of failures under test

The goal of minimising censored data has led to the common practice within standard protocols of allowing re termination and retest following a termination failure or flashover. Although very attractive, this approach introduces a fundamental complication in any subsequent analysis; namely that the retested sample will have a shorter length than the uncensored first tests. Thus we would inherently expect from the principles of weakest link failures that these samples would tend to have higher breakdown strengths as they will have a lower probability of containing the weaker links [6]. This effect is described mathematically in Equation 1 [6] and shown experimentally in Figure 3 [9]. When the time of testing and the test lengths are held constant, then Equation 1 can be re arranged to describe how the Weibull Scale Parameter is modified by a change in insulation volume (Equation 2).

$$P_f = 1 - \exp\left(\frac{E}{\alpha}\right)^a \left(\frac{t}{t_c}\right)^b \left(\frac{l}{l_{ref}}\right) \quad \textbf{Equation 1}$$

$$\alpha_{\ actual} = \alpha_{ref} \left(\frac{V_{ref}}{V_{actual}}\right)^{1/\beta} \quad \textbf{Equation 2}$$

Where P is the probability of failure; α, t_c are Weibull Scale Parameters; *a, b* & β are Weibull Shape Parameters, *ref* and *actual* refer to the lengths (i) volumes (V) tested.

This means that smaller devices or shorter cables would be expected to give higher breakdown strengths (Figure 3). This effect is also seen in high voltage cables [10]

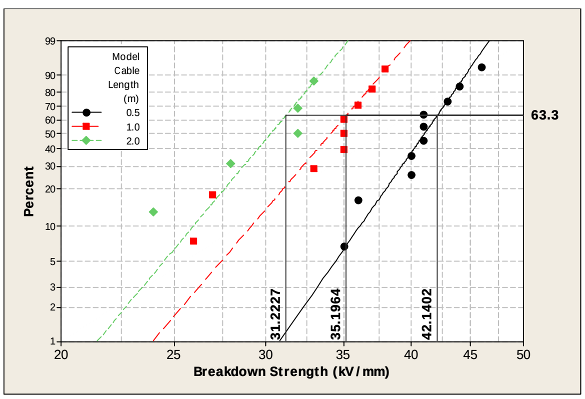

Figure 3 Breakdown strength (mean) of model cables (1.5 mm wall) of different lengths after wet ageing for 1000 hours [9]

The consequence of retesting and treating these data in the same way as the first failures is shown in Figure 4. Figure 4 shows 10 breakdown data after one year of ageing. These data experienced three censored / retested data and a single omitted datum (mechanical damage). Overall 60% of the first tests resulted in the desired type of failure; 40% did not fail.

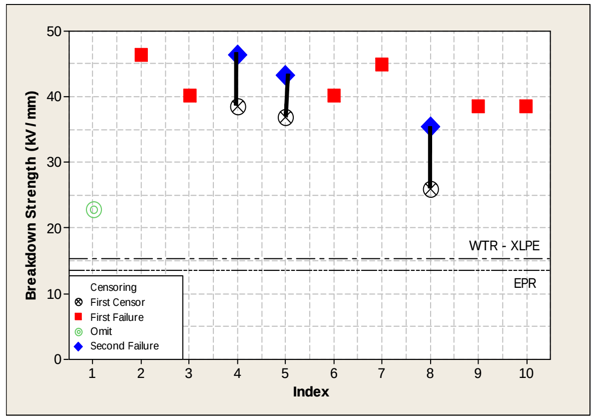

Figure 4 Sequence of 10 breakdown test data after one year of wet ageing. Data are segmented for first failures – within correct active length, first censor – no failure within active length and second failure – failure within a short active length after a censor. The cable associated with the omitted point suffered mechanical damage within the test programme. The vertical lines show the range between initial censored value and the retest on the shorter length. The horizontal lines represent the minimum values defined in ICEA at 360 days.

All of this is somewhat theoretical in the context of the originally envisaged approval testing; as the goal is to establish that the performance of a design is considerably above a minimum value. In short, there is not too much interested in the absolute performance to any great accuracy. However if users are interested in an accurate assessment of the performance, as we would be in the case of comparative or research tests; then the simple inclusion of the retest data is inappropriate.

The correct approach is to recognise that, for the retested samples, we do not know the breakdown strength for the target length [5, 6, 8]. What we do know is that the strength is somewhere between the first (censored but correct length strength) value and the retest (good failure but shorter length). These data can be treated in most competent analysis programmes by defining them as “intervally censored data”. With this approach the standard Weibull Parameters can then be obtained (Figure 5). It is important to note that although the Censored Data are not usually plotted, they do participate in determining the confidence intervals, which in turn are used to establish the statistical strength of conclusions.

Figure 5 shows the data from Figure 4 in Weibull format. The parameters are presented in Table 2. The analyses have been carried out for four ways to treat the data which include:

a. first tests as ‘real’ failures
b. first and any second retests as ‘real’ failures
c. censored first tests and omitted data as simple censors – no retests included
d. omitted data as simple censored and first censor and second failure data as intervally censored data

Table 1 presents the data for the options a to d.

Table 1 Data sets derived from Figure 4 and used for analyses in Figure 5

	Breakdown Strengths for selected treatments (kV/mm)			
	a	**b**	**c**	**d**
Failures	*10*	*10*	*6*	*6*
Censors	*0*	*0*	*4*	*4*
1	23	23	>23	>23
2	47	47	47	47
3	40	40	40	40
4	38	47	>38	>38 <47
5	37	43	>37	>37 <43
6	40	40	40	40
7	45	45	45	45
8	26	35	>26	>26 <35
9	39	39	39	39
10	39	39	39	39

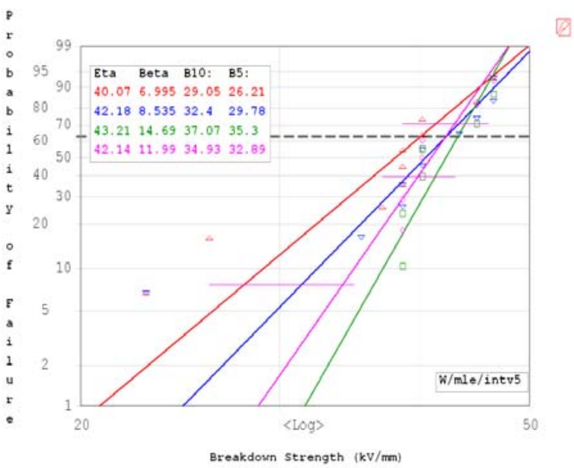

Figure 5 Weibull analysis of the data from Figure 4 & Table 1 segregated into the identified rules and data sets – a, b, d & c, reading left to right. The horizontal lines serve to show that range of the intervally suspended data for data set d .

Table 2 Weibull Parameters for the analyses in Figure 5

	Shape Parameter	**Stress at selected failure probabilities (kV/mm)**		
		63% Scale Parameter	**10%**	**5%**
a	7	40.1	29	26.2
b	8.5	42.2	32.4	29.8
c	14.7	43.2	37	35.3
d	12	42.1	35	38.9

This figure shows that the most appropriate analysis (third curve in Figure 5, d in Table 2) provides very different results than the alternate approaches. Most importantly, the usual analyses for the data would indicate that the Weibull Scale parameter (63% failure) is under estimated. The underestimate could be as large as 5% of the true value. Perhaps more importantly the Shape parameter (gradient of the curve) is quite different. This would lead investigators to make inappropriate conclusions about the mechanisms of failure. This element is rarely considered in approval testing but is a very crucial part of many reasearch programmes as the mechanism of failure determines the likelihood of the first failures, either in terms of long cable lengths or early failures.

NUMBER OF BREAKDOWN SAMPLES

The number of samples employed in an analysis is a critical balance between the number required to complete the desired goal and the cost of testing. In general, the normal cable approval protocols [1, 2] require only the grossest of information, as they require confirmation of performance above a certain level, and thus the smallest number of samples. Therefore, in general, it is clear that if a test programme is trying to identify finer details than required in an approval process, then it will most often require more samples.

The exact number of samples can be guided by two considerations: a) sufficient samples to accommodate the expected level of censored data and b) the inherent scatter in the measured data.

It is often argued that increasing sample size is prohibitive in terms of test costs. Whilst it is true that costs increase, this is not a linear function of sample numbers: 25% increase in samples does not lead to a 25% increase in cost. This is especially relevant in the case of censored data; even in existing programmes, a retest would be required yet it would be much more appropriate to conduct an additional test on the spare aged cable rather than perform a more questionable retest on the shortened sample that had failed. Furthermore, any increase in cost or complication is almost certainly less costly than an inappropriate or misleading experiment that might ultimately have to be repeated**.**

Inherent Scatter

Scatter is an inherent issue in all test data; but is very significant with breakdown step tests. However there are conditions when they can appear highly un-scattered. This case is when step voltage tests are employed with aged cables. In this case more than one failure can occur on a single step. This feature is displayed in Figure 6 at 40 & 37 kV/mm for H & L respectively. In general, inspection of the times that failures occur within a data set shows that they are not of the same performance, however there is almost no way to represent this different performance. The cause of this is the traditionally large voltage steps. Analytically this presents a problem as we are trying to fit a distribution to points which have the same failure level: Index 10 of H & Index 7 of L. The solution for the breakdown test phase is to maintain the overall voltage ramp rate but to use smaller time / voltage steps: steps of 5 kV every 5 minutes would be replaced by, for an example, 1kV every minute. This approach provides the best chance of providing discriminating data. This issue is most prevalent at the longest ageing times as ageing tends to both lower the cable strength and reduce the scatter in the data.

Many studies employ Confidence Interval or even Monte Carlo calculations [6,8] to assess the magnitude of the inherent scatter in the estimates of performance. Generally a single set of parameters is chosen and then many (>100) datasets are then generated. The spread of the analyses of these datasets is then taken as a representation of the scatter. In the paper we will address this from a different viewpoint; rather than computing many datasets we have taken two sets of 5 first measurements and then computed all of the possible ICEA style (where three cable failures are required) evaluations. This approach enables us to examine how a large number of sequential evaluations might be interpreted if only three failures had been used.

Figure 6 shows data for two data sets H & L. These sets contain five data but appear to only have four failures, However there are co incident test data at 40 & 37 kV/mm for H and L respectively. The coincidences are caused by the use of step tests.

Set H contains two censored data (open symbols). Thus when generating the sets of three for the ICEA style analyses four of the groups contain only a single un ambiguous failure. Analysis can proceed if there is sufficient prior experience using a Bayesian approach (assumed shape parameter)[7,8]. However, this foregoes the chance of determining mechanistic information provided by the Weibull Shape Parameter. In this situation, it is clear that an additional aged cable would be invaluable to determine the correct performance.

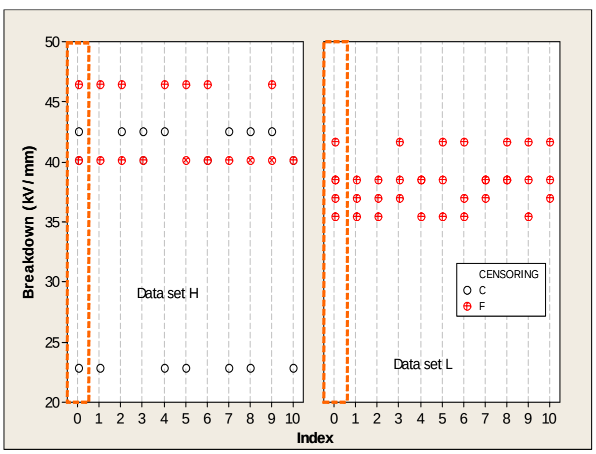

Figure 6 Two sets (H & L) of five final sample breakdown data (Index 0), which have been separated out into 10 sets of three data to comply with the format of the ICEA tests (Indices 1 to 10). F & C indicate Failed & Censored Data for the first tests; for simplicity the retest results on short samples for set H have been omitted.

Weibull analyses have been completed for the ten three member data groups of set L in Figure 6. These analyses (Figure 7) can be completed in a straightforward manner as this particular set contains only true failures. Attempting this type of analysis for set H would be exceptionally difficulty and serves to further re enforce the usefulness of additional samples. It is instructive to note that five sets contain only one failure and three sets have two failures.

The bold line in Figure 7 represents the analysis of the full data set which has a scale parameter of 39.3 kV/mm. The vertical lines represent the individual scale parameters which are scattered around this value by -4% & +2%. One profound consequence of such an analysis is the discrimination it reveals for the standard test protocols. In this case it indicates that groups of three failures drawn from the same dataset, without recourse to Monte Carlo methods, could give results between 37.6 & 40.4. Consequently if the usual three sample data groups are used in an evaluation programme then the expected difference should be of the order of twice the data range (6 kV/mm) for there to be a reasonable chance of achieving discrimination. Of equal importance is the variation in Weibull Shape parameter (gradient of the curve); inspection of the 10 data groups clearly shows that there are a variety of gradients. This would normally be interpreted as the groups failing by different mechanisms. However this cannot be the case as the data are derived from the same single mechanism, five member dataset.

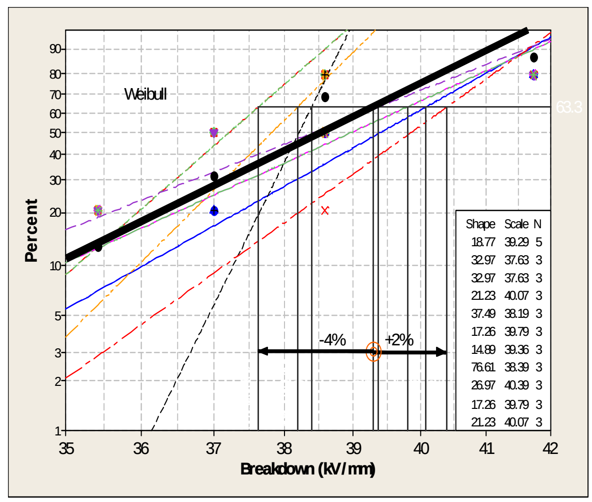

Figure 7 Results of the Indices 0 to 10 for Set L presented in a Weibull format. The bold line represents the fit of the completefive failure points. The vertical drop lines display the position of the Weibull scale parameters. Weibull Shape, Scale Parameters and numbers are displayed in the table for indices 0 to 10.

Accommodating censored data

ICEA and CENELEC cable ageing protocols require a minimum of three and six "good" cable breakdowns to perform the assessments. Experience shows that cable ageing out to one, two & five year results in censored portions of 35, 30 & 5 % respectively for the final breakdowns. Thus to ensure, on average, that there is the minimum of "good data" then the initial number of samples should be increased, at least, by these fractions (Table 3). This consideration becomes even more important as ageing times extend, as the incremental cost becomes less significant when viewed against the costs of a failed evaluation which has taken two years to complete.

Table 3 Portion of results censored and the compensating samples to be aged. Results are prfesented for selected ageing times

Years ageing	Portion Censored (%)	Number of final failures required / Number of test samples to be aged to normally achieve the required failures
0	35	3 / 5 6 / 9
1	30	3 / 5 6 / 8
2	30	3 / 5 6 / 8
5	5	3 / 4 6 / 7

CABLE SIZE

Medium voltage cables are designed and operated at generally similar stresses, even though the operation voltages may range from 10 to 35 kV. This has led to a position within standards whereby either a single design is tested to gain approval for the whole MV arena or any suitable design may be selected. However, there is a wide range of conductor sizes at MV such that when the test length is kept constant (as is the case with all tests) there will be significant differences in the volumes of the insulation and areas of screens tested. When moving into more detailed investigations consideration must be given to the freedom permitted within the approval protocols. The importance of cable size (voltage class – wall thickness; test length) is clear from the theory represented in Equation 2: a smaller cable might be expected to provide better performance due to its reduced size.

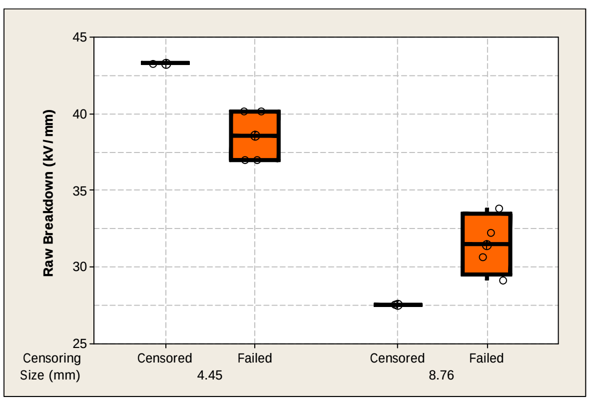

Figure 8: Average breakdown strength of cables with different wall thicknesses. The same production methods, insulation systems, test methods and conductor size were used for all tests

In the approval arena, this would seem to suggest that it is less onerous to achieve the required success criteria with smaller volume units. Obviously, this could lead to an incorrect interpretation in some cases. These considerations are particularly significant when present day tests are compared with historical references or “data mined results”.

In these cases, it is our experience that there are most often quite considerable differences in sizes that can complicate or even compromise the analyses.

This consideration means that the variation of size should be controlled within an experiment such that the desired features are not masked. Where the control of size is not practical then additional factors must be added into the analyses to avoid in appropriate or incorrect conclusions.

ANALYTICAL TECHNIQUES

In our experience the cable ageing research tests conducted today are often designed to simultaneously investigate many features. Consequently, simple comparisons of mean strengths or Weibull Scale Parameters are not of themselves sufficient. Generally, project sponsors wish to know not just if a system complies with the specification minimum, but in addition how significant is this improvement. Therefore, we have found that ANalysis Of Variance (ANOVA) are often invaluable in determining the magnitude and significance of factors that influence the test results. Although this is a powerful and useful technique there are instances (especially with endurance tests) when Non Parametric (not based on an assumed distribution) methods are appropriate.

Figure 9 shows the results of the analysis of three cables manufactured using different semicon materials [11]. Inspection of the mean and Weibull Scales (not shown) would indicate that there are differences between the three material systems. ANOVA shows that in fact materials A & C and B & C are not all significantly different. In fact, it is only the A & B combination that displays a difference that is significant – 99 to 99.7% significant. Clearly in the absence of an ANOVA the costs associated with a change from B to C (80 to 90%) or A to C (94 to 97%) might have been incurred without gaining a significant benefit.

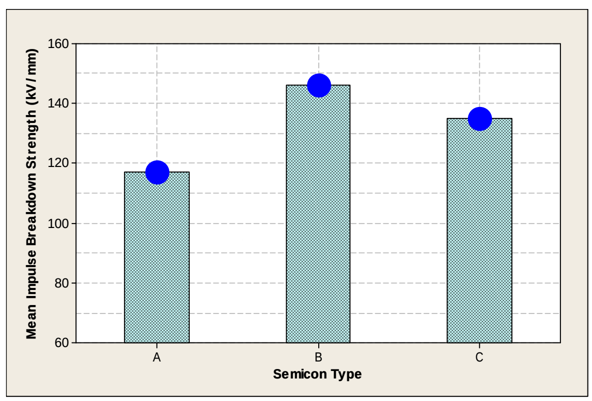

Figure 9 Mean impulse strength of cables using three different semicon materials [11]

A general scheme that we have come to find very appropriate is to complete both distribution based and distribution free analyses. In most cases these are in agreement and the findings are thus clear.

CONCLUSIONS

This paper discusses a number of the issues that need to be addressed when conducting cable ageing experiments to gain a better understanding of cable performance. It recognizes that approval protocols are well served at present due to the fact that they are seeking to assure that the cable performance is above a required minimum.

However a number of straightforward additions should be made to the standard approval protocols to make then better suited to determining the performance of the cables. These improvements in test approaches include:

- ☒ Increased number of samples in the ageing phase to allow for the potential censored data when the final breakdowns are completed
- ☒ Treat termination failures and flashovers as censored data
- ☒ When a censored result occurs, test a spare aged sample in preference to retesting a shortened length sample
- ☒ Retests on shortened lengths should be treated as Intervally Censored Data
- ☒ Subsequent tests on a spare aged sample should be treated as a true failure with the originally censored data being treated as a Right Censored Data (exact strength not known but known to be above this value)
- ☒ Use smaller voltage / time steps whilst retaining the same overall rate of rise to reduce the occurrence of data with tied breakdown strengths
- ☒ Analyse the breakdown results using a range of robust statistical techniques (ANOVA & Kruskal-Wallis) rather than comparing central values (mean or Weibull Scale) of magnitude
- ☒ Carefully consider making inferences when the data set is comprised of cables with differing dimensions (length, wall, conductor)
- ☒ Prior to embarking on a test programme it is critically important to assess whether the magnitude of the expected difference between designs or ageing is sufficiently large to be detectable by the chosen sample sizes

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