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DIELECTRIC COMPARISONS OF DIFFERENT TYPES OF ARAMID INSULATION

SUMMARY

This paper summarizes the results of a number of very different test programs designed to characterize the dielectric performance of three families of aramid paper products. The first part of the testing includes a range of papers that seem well suited to layer type liquid-immersed transformer winding applications. The rapid rise breakdown testing includes multiple thicknesses of the three aramid families that vary in density and surface texture. Wire wrap insulation is the focus of the second part of the testing examined. The results include several different types of test programs, ranging from single flat sheet to multiple flat sheets to actual wire wrapped with multiple thicknesses of the sample insulation. In this series, both rapid rise and impulse breakdown testing is reported. Where possible, statistical analysis was used to make comparisons.

Key words: aramid, dielectric strength, insulation testing, liquid-immersed transformer, breakdown testing

1. INTRODUCTION

High-temperature aramid insulation has been used for many years in liquid-immersed transformer applications. A number of papers have presented some of the supporting dielectric test data for both paper and board. However, most of this information was developed for wire wrap and pressboard insulation for applications in power transformers, such as high-temperature mobile substations and for on-board traction applications in high-speed trains. Very little has been published on test results in liquid for other aramid paper types. Although most of these other products were originally designed for dry-type applications in motors and transformers, they are beginning to see widespread use in liquid-immersed transformer applications as well.

IEC and IEEE standards that address high-temperature liquid-immersed transformers are currently under development, signaling an increased global interest in applications, such as wind turbine step-up and lightweight pole mounted and platform mounted transformers. These units and new designs in traction on-board transformers, which use layer-type windings, are better suited to these alternate paper types. Accordingly, the dielectric performance in liquids has become increasingly more important for optimized usage. This paper presents the results of several recent research studies that will help to fill in many of the dielectric information gaps and will begin characterizing a more complete dielectric picture of aramid products in various dielectric liquids, under different test configurations. For reference purposes, a comparison will also be made to a limited range of conventional kraft insulation types.

2. TEST DESCRIPTION AND ANALYSIS

2.1. Layer Insulation

Aramid paper is available in a range of thicknesses for several different product families that vary in density and surface texture. These products were designed for transformer, motor slot liner and other dry-type layer winding applications, but are suitable for layer type liquid-immersed coil winding applications as well. In this test series, high-density and medium-density aramid paper families were tested to determine dielectric capability in mineral oil. The high-density products were further divided into smooth surface and textured surface families. In most cases, the samples were also selected from three different rolls in order to account for some of the inherent manufacturing variability in the paper making process. Five samples were tested from each roll, for a total of fifteen samples for each thickness. Note that multiple rolls were not available for the samples of the kraft paper and the 0,18 mm medium density aramid paper (marked with an asterisk in the tables). Samples for these papers were all taken from the same roll.

Logically, the data set should be divided into groups. Each group is defined by density, surface texture and thickness. Papers measuring less than about 0,10 mm typically target the wire wrap insulation application. These will be addressed later. The medium thickness papers range from about 0,10 mm to less than 1,0 mm. Since pressboard thicknesses begin at about 0,50 mm, there is some overlap for the two products that are made very differently. Pressboard, however is not part of this investigation.

2.1.1. Test Protocol

The flat sheet samples were dried, impregnated with mineral oil and then tested between two 25 mm diameter flat electrodes, according to IEC 60243-1[1]. During the rapid rise test, the 50 Hz voltage was raised linearly with time. The rise time was chosen in such a way that the breakdown occurred within 10 to 20 seconds after the start of the test. Each sample was cut to the same dimension of 100 mm x 100 mm, with one test per sheet.

During the tests, the mineral oil quality was monitored by periodically testing the dielectric strength and when necessary, the mineral oil was filtered and dried. For additional comparison purposes, the density of each sample is shown in Tables I, II, III and IV along with the permittivity calculated for mineral oil. The permittivity is also calculated with synthetic ester liquid, since both natural and synthetic esters have seen increasing interest. The permittivity is calculated according to the formula described in the book, Transformerboard II[2].

2.1.2. Test Data

Table I - High-Density Aramid - Smooth Surface (HDS)

Thickness (mm)	**0,13**	**0,18**	**0,25**	**0,38**	**0,51**	**0,76**
Measured Mean Thickness (mm)	0,130	0,182	0,260	0,385	0,511	0,762
Density (g/cm^3)	0,87	0,95	0,96	1,03	1,06	1,10
Permittivity – Mineral Oil	3,24	3,34	3,36	3,45	3,49	3,55
Permittivity – Ester Liquid	3,69	3,73	3,74	3,78	3,80	3,82
Mean Breakdown Stress (kV/mm)	84,2	79,7	75,5	72,7	68,6	66,7
Breakdown Stress Std Deviation (kV/mm)	4,42	3,85	2,95	2,86	2,35	2,66
Minimum Breakdown Stress (kV/mm)	74,6	74,5	71,0	69,0	64,9	60,1

Table II - High-Density Aramid - Textured Surface (HDT)

Thickness (mm)	**0,18**	**0,25**	**0,38**
Measured Mean Thickness (mm)	0,193	0,262	0,408
Density (g/cm^3)	0,94	0,95	0,98
Permittivity – Mineral Oil	3,33	3,34	3,38
Permittivity – Ester Liquid	3,73	3,73	3,75
Mean Breakdown Stress (kV/mm)	87,5	86,5	77,4
Breakdown Stress Std Deviation (kV/mm)	2,91	4,14	1,72
Minimum Breakdown Stress (kV/mm)	83,1	80,1	74,8

Table III - Medium-Density Aramid (MD)

Thickness (mm)	0,18 *	0,25	0,38	0,51
Measured Mean Thickness (mm)	0,167	0,245	0,367	0,489
Density (g/cm^3)	0,68	0,67	0,67	0,67
Permittivity – Mineral Oil	3,00	2,98	2,98	2,98
Permittivity – Ester Liquid	3,58	3,57	3,57	3,57
Mean Breakdown Stress (kV/mm)	90,5	79,4	70,4	69,9
Breakdown Stress Std Deviation (kV/mm)	4,59	5,47	4,21	2,24
Minimum Breakdown Stress (kV/mm)	80,8	67,1	62,5	66,3

Table IV – Kraft Paper (K)

Thickness (mm)	0, 50
Measured Mean Thickness (mm)	0,464
Density (g/cm^3)	1,15
Permittivity – Mineral Oil	4,35
Permittivity – Ester Liquid	4,66
Mean Breakdown Stress (kV/mm)	59,0
Breakdown Stress Std Deviation (kV/mm)	1,95
Minimum Breakdown Stress (kV/mm)	54,7

2.1.3. Layer Insulation Data Analysis

The usual statistics of mean breakdown stress, standard deviation and lowest breakdown stress provide a means of comparing different materials. Figure 1 compares the breakdown stress for the three different aramid families versus the product mean measured thickness. The single kraft test point is also shown for reference. As is typical for solid insulation, the breakdown stress for aramid products declines as the product thickness increases. Comparing the densities, it is interesting to note that the breakdown stress for the medium density product (MD) is not significantly different from the high-density product with the smooth surface (HDS). However, the high-density aramid family with the textured surface (HDT) does show an apparent improvement compared to both the medium density family and the high-density family with smooth surface.

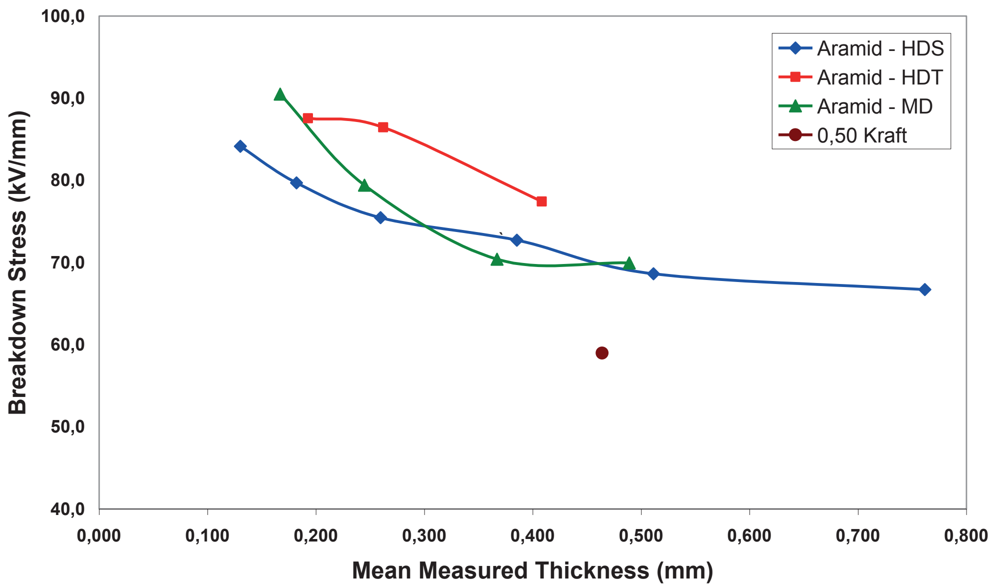

Figure 1 – Layer Insulation Breakdown Stress vs. Thickness

The density also greatly affects the permittivity of all paper insulation. Compared to kraft paper, the aramid products have permittivity closer to that of the dielectric medium, especially the esters where a 3,2 is typical. However, the medium density family with permittivity of 3,0 for mineral oil and 3,6 for ester is even closer due to the lower density, while the dielectric strength is maintained.

2.2. Wire Wrap Insulation

Aramid sheet insulation designed for wire wrap insulation applications typically differs from thicker paper structures and from kraft paper, with lower density and lower permittivity. This section compares the breakdown stress of a new aramid wire wrap insulation, specifically designed for use in liquid-immersed transformer applications, with the original aramid wire wrap and with kraft paper. Both the new aramid and the original aramid papers belong to the high-density smooth surfaced product family. Three separate test programs will be reviewed in characterizing the new wire wrap insulation and different techniques will be used for comparison.

2.2.1. First Test Series

The first series was part of the layer insulation test series and included the new aramid paper and a kraft paper of similar thickness. The test conditions were the same as previously described and the results are shown in Table V along with reference data for the original aramid paper, which was not part of the test series. The table also includes key parameters of density and permittivity.

In analyzing insulation breakdown test data, IEC 62539[3] considers a data set of less than fifteen to twenty breakdowns to be a small set. Consequently this data set of 14/15 breakdowns is marginal for statistical analysis, but should provide a good indication. The guide also states the following: “Distributions for electrical breakdown include Weibull, Gumbel and lognormal. The most common for solid insulation is the Weibull and is the main distribution described in this guide. It is found to have wide applicability and is a type of extreme value distribution in which the system fails when the weakest link fails.”

A typical Weibull plot is shown in Figure 2 and provides a good visual indication of the quality of fit, based on how closely the data points fit the curve. The curve is useful in characterizing a test series and especially in comparing two insulation materials. In this case the new aramid paper is plotted as an example. The basic parameters of the curve are the scale and the shape, where the scale parameter is analogous to the mean value in the more familiar normal distribution model and is designated by the reference line drawn through the 63,2 probability percentile on the curve. The shape parameter is analogous to the inverse of the standard deviation and is a measure of the range or spread of the breakdown values. These parameters are also shown in Table V.

Table V – Aramid and Kraft Wire Wrap

	Kraft Paper	Aramid - New	Aramid - Original
Actual Mean Thickness (mm)	1,97	2,07	2,33
Density (g/cm^3)	0,96	0,71	0,72
Permittivity – Mineral Oil	3,94	3,03	3,05
Permittivity – Ester Liquid	4,39	3,59	3,60
Mean Breakdown Stress (kV/mm)	72,3	83,5	N/A
Breakdown Stress Std Deviation (kV/mm)	6,68	6,47	N/A
Minimum Breakdown Stress (kV/mm)	58,6	72,6	N/A
Weibull Distribution Shape	15,0	15,23	N/A
Weibull Distribution Scale	75,0	86,4	N/A

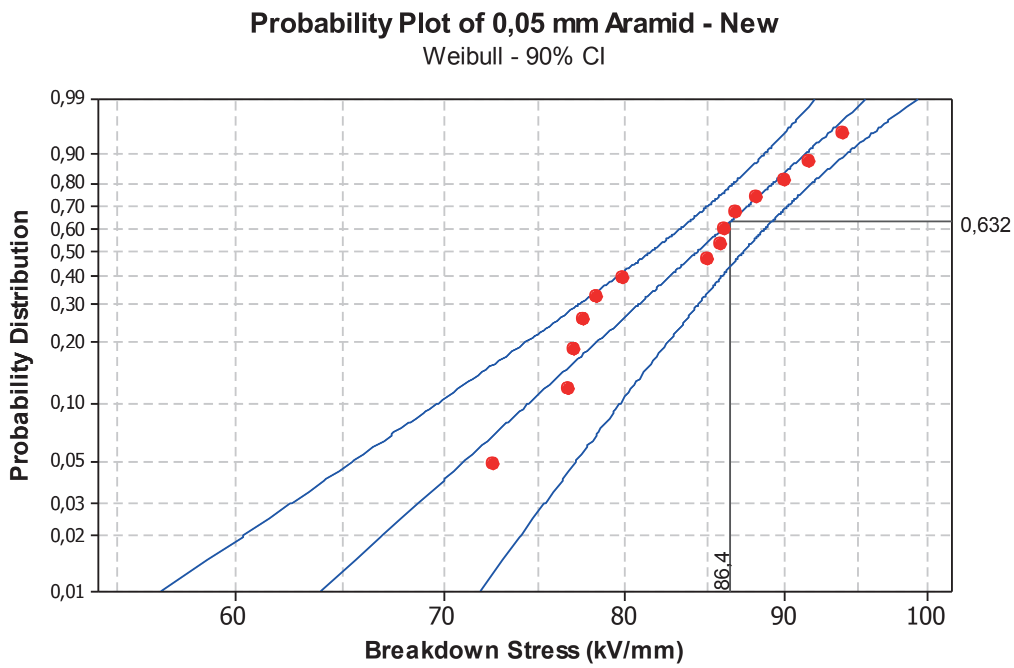

Figure 2 – Weibull Probability Plot of New Aramid Breakdown Stress

2.2.2. Second Test Series – Rapid Rise

The second series was also a flat sheet test program but included impulse breakdown as well as rapid rise breakdown. Multiple sheets were tested in a medium of both mineral oil and ester liquid, which should be a better representation of actual application, since an insulated wire would always have multiple thicknesses. The flat sheet samples were dried, impregnated with the test medium and then tested between unequal diameter electrodes of 25 mm and 75 mm, according to IEC 60243-1. During the rapid rise test, the 60 Hz voltage was raised linearly with time. The rise time was chosen in such a way that the breakdown occurred within 10 to 20 seconds after the start of the test. Each sample was cut to the same dimension of 300 mm x 300 mm, with five tests per sheet and a total of ten tests for each condition.

Table VI – Rapid Rise Breakdown in Mineral Oil

Number of Insulation Sheets Tested		1	3	4	5	10	Mean
Aramid New	Mean Breakdown Stress (kV/mm)	68,4	76,0	68,8	68,6	67,5	69,8
	Minimum Breakdown Stress (kV/mm)	48,0	70,9	66,1	64,9	62,4	
	Breakdown Stress Std Deviation (kV/mm)	9,2	3,1	2,5	2,7	2,9	4,0
	Number of Tests	10	10	10	10	10	
Aramid Original	Mean Breakdown Stress (kV/mm)	49,3	72,4	67,8	64,1	52,0	61,1
	Minimum Breakdown Stress (kV/mm)	39,7	69,6	64,7	60,3	48,9	
	Breakdown Stress Std Deviation (kV/mm)	5,6	1,7	1,6	3,1	1,7	2,7
	Number of Tests	10	10	10	10	10	

Table VII – Rapid Rise Breakdown in Synthetic Ester

Number of Insulation Sheets Tested		1	3	4	5	10	Mean
Aramid New	Mean Breakdown Stress (kV/mm)	64,3	77,8	72,8	70,7	76,4	72,4
	Minimum Breakdown Stress (kV/mm)	53,9	70,8	68,6	62,1	67,6	
	Breakdown Stress Std Deviation (kV/mm)	6,5	4,0	2,8	3,9	3,3	4,1
	Number of Tests	10	10	10	10	10	
Aramid Original	Mean Breakdown Stress (kV/mm)	63,1	75,0	69,2	66,8	69,7	68,8
	Minimum Breakdown Stress (kV/mm)	46,4	65,0	60,7	63,8	65,0	
	Breakdown Stress Std Deviation (kV/mm)	11,6	5,2	5,5	2,1	3,1	5,5
	Number of Tests	10	10	10	10	10	

2.2.3. Second Test Series – Impulse

For the impulse voltage tests, the flat sheet samples were dried, impregnated with the test medium and then tested between two 50 mm diameter flat electrodes. The voltage of successive sets is increased in magnitude until breakdown of the test specimen occurs, according to IEC 60243-3[4]. The standard wave shape is a 1,2 by 50 μs wave, reaching peak voltage in approximately 1,2 μs and decaying to 50% of peak voltage in approximately 50 μs after the beginning of the wave. This wave is intended to simulate a lightning stroke that may strike a system without causing failure on the system. During these two test series, the test medium quality was monitored by periodically testing the dielectric strength and when necessary, the dielectric liquid was filtered and dried.

Table VIII – Impulse Breakdown in Mineral Oil

Number of Insulation Sheets Tested		1	3	4	5	10	Mean
Aramid New	Mean Breakdown Stress (kV/mm)	128,0	137,2	175,3	171,6	157,3	153,9
	Minimum Breakdown Stress (kV/mm)	115,9	130,0	157,1	160,4	148,5	
	Breakdown Stress Std Deviation (kV/mm)	8,3	5,4	9,8	7,8	6,7	7,6
	Number of Tests	9	6	10	10	10	
	Impulse Ratio	1,87	1,81	2,55	2,50	2,33	2,21
Aramid Original	Mean Breakdown Stress (kV/mm)	111,3	118,5	146,4	155,3	145,7	135,4
	Minimum Breakdown Stress (kV/mm)	82,1	102,5	124,6	140,0	132,7	
	Breakdown Stress Std Deviation (kV/mm)	20,7	8,4	12,2	10,8	7,5	11,9
	Number of Tests	9	10	8	10	10	
	Impulse Ratio	2.26	1.64	2.16	2.42	2.80	2.26

Table IX – Impulse Breakdown in Synthetic Ester

Number of Insulation Sheets Tested		1	3	4	5	10	Mean
Aramid New	Mean Breakdown Stress (kV/mm)	125,0	137,4	184,4	176,6	145,7	153,8
	Minimum Breakdown Stress (kV/mm)	103,9	126,0	168,0	168,2	137,8	
	Breakdown Stress Std Deviation (kV/mm)	12,7	5,6	10,8	6,6	4,5	8,1
	Number of Tests	10	9	10	10	10	
	Impulse Ratio	1,83	1,81	2,68	2,57	2,16	2,21
Aramid Original	Mean Breakdown Stress (kV/mm)	105,5	125,6	142,6	158,1	135,4	133,4
	Minimum Breakdown Stress (kV/mm)	84,6	99,9	115,0	140,4	123,5	
	Breakdown Stress Std Deviation (kV/mm)	13,6	11,1	14,6	9,5	6,2	11,0
	Number of Tests	10	10	10	10	10	
	Impulse Ratio	2,14	1,74	2,10	2,47	2,60	2,21

2.2.4. Third Test Series

The third series uses a special test setup first published by Prevost and Franchek[5]. The test series is designed to more closely simulate the wire-to-wire stresses of a power transformer winding and is the best representation of the three test series presented. The wire-to-wire tests were performed on wire wrapped with the new aramid wire insulation. The samples included wire wrapped with four different insulation builds. For the test, two straight sections of wire are cut to length and each end is formed to the shape of a Rogowski curve. The wires are then tested back-to-back. The specially shaped ends force the stress to the flat central region of the wire contact, reducing false breakdown in the oil wedge at each end. This test method is much more representative of actual transformer application than flat electrode testing and includes the mechanical stresses applied to the insulation during the wrapping process. The fixture is then submerged in a plastic container filled with the dielectric liquid. Figures 3 and 4 show photos of the test fixture.

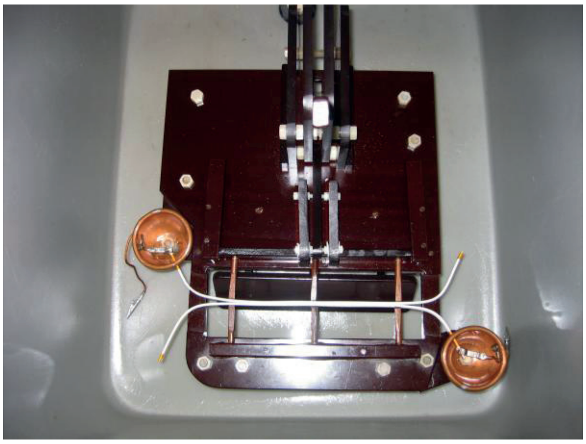

Figure 3 – Wire-to-Wire Test fixture

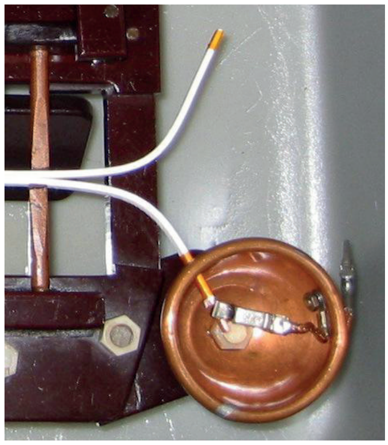

Figure 4 – Detail of Wire Shape

For this series, mineral oil was the dielectric liquid. The quality of the oil was monitored by periodically testing the dielectric strength and when necessary, the oil was filtered and dried. This type of test has been used over many years and the results of this test series are shown in Tables X and XI.

Table X – Rapid Rise Wire-to-Wire

Insulation Thickness (mm)	0,31	0,41	0,81	1,22	Mean
Mean Breakdown Stress (kV/mm)	62,3	59,0	47,5	42,3	52,8
Minimum Breakdown Stress (kV/mm)	53,5	56,1	43,2	39,8	
Breakdown Stress Std Deviation (kV/mm)	5,6	2,0	2,0	1,8	2,9
Number of Tests	17	14	14	15	

Table XI – Impulse Wire-to-Wire

Insulation Thickness (mm)	0,31	0,41	0,81	1,22	Mean
Mean Breakdown Stress (kV/mm)	145,0	142,4	122,7	110,4	130,1
Minimum Breakdown Stress (kV/mm)	131,0	124,2	114,7	103,0	
Breakdown Stress Std Deviation (kV/mm)	8,2	9,5	4,6	3,7	6,5
Number of Tests	13	14	14	15	
Impulse Ratio	2,33	2,41	2,58	2,61	2,48

2.2.5. Wire Wrap Insulation Data Analysis

In the first test series, the breakdown stress data in Table V suggests a clear improvement of the aramid over the kraft in dielectric strength, although several factors must be considered. Most importantly, this is only one of many readily available kraft papers and these products do vary in performance. The data set is also quite small and only marginally adequate. However, a comparison by Weibull plot is possible, since the test conditions were the same, which is one of the considerations for using this comparison technique. The other main condition is to determine whether the data is a good fit to the Weibull distribution.

To test the adequacy of using the Weibull distribution model, IEC 62539 suggests determining the correlation coefficient for the data set and then checking to make sure this value is greater than the critical correlation coefficient taken from the graph in the document on goodness-of-fit for a two-parameter Weibull distribution. This correlation is a function of the number of specimens broken down.

The correlation coefficient, R2 equals 0,930 for the aramid paper and 0,964 for the kraft paper. This compares to a critical correlation coefficient value of 0,929 based on 14 samples. Accordingly, the fit is adequate, although only marginal for the aramid paper. The test then for comparison, as advocated in IEC 62539 is taken from Weibull who suggested that: "a useful hypothesis test is to examine whether there is overlap in the confidence limits at a given percentile and he suggested the 10th percentile for this purpose".

The result is shown in Figure 5 with the region of interest circled in red. Note that while there is no overlap, the results are certainly not conclusive. Based on this test set, the two products are statistically different at the 10th percentile, but not by much. However, at the lower percentiles the performance of the two products is statistically not different, since the confidence limits overlap in this region. Although a comparison is generally made at the mean value, or in the case of a Weibull distribution, the scale at a probability percentile of 63,2, it is the lower percentiles well below 10 that define the working voltage stress capability of a material.

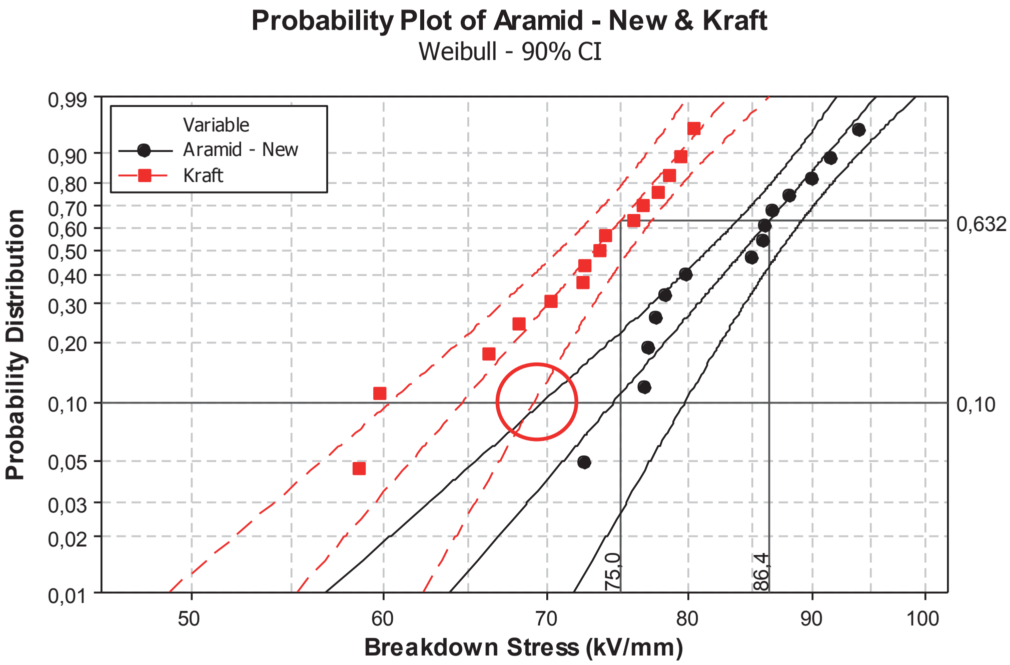

Figure 5 – Weibull Probability Plot Comparison

In the second test series, the mean value of the breakdown stress for all of the rapid rise tests is calculated for a given liquid and then the results for the new and original aramid papers are compared. The data does not fit the Weibull distribution model, but considering the standard deviation for the synthetic ester test, the results indicate the two products are not statistically different. For the mineral oil test, there is a difference, but it is small. The test series also indicates the difference in the liquid medium has no affect on the dielectric properties of the two products for the rapid rise test.

The same comparison is made for the impulse test results, except that the results are more conclusive than for the rapid rise test. While again, there is no difference in the dielectric strength due to the liquid test medium, there is a significant difference between the impulse breakdown stresses for the two products suggesting about a 15% improvement for the new aramid paper compared to the original paper. From this test series, the impulse ratio is determined by dividing the impulse test results by the rapid rise test results. The approximate 2,2 value is not very different from that of typical kraft paper and the commonly assumed value of 2,4.

Table XII compares the breakdown test results of the third test series to historical test results for the original aramid, the high-density textured aramid and the mean values of test results for kraft products from five different manufacturers. Again, the data sets do not adequately fit the Weibull distribution model, but a comparison of the mean rapid rise breakdown stress values with the standard deviation shows there is no statistical difference between the aramid products. However, the comparison indicates that all three aramid products show an improvement over the mean values of the five kraft products. This can be seen visually in Figure 6.

Table XII – Comparison of Historical Breakdown Test Data

	Rapid Rise		Impulse		
	Breakdown (kV/mm)	**Std Dev (kV/mm)**	**Breakdown (kV/mm)**	**Std Dev (kV/mm)**	**Impulse Ratio**
Kraft	40,1	2,3	89,3	8,4	2,25
Aramid – Original (HDS)	47,0	2,2	111	5,5	2,42
Aramid (HDT)	52,0	2,8	135	7,5	2,63
Aramid - New	52,8	2,9	130	6,5	2,48

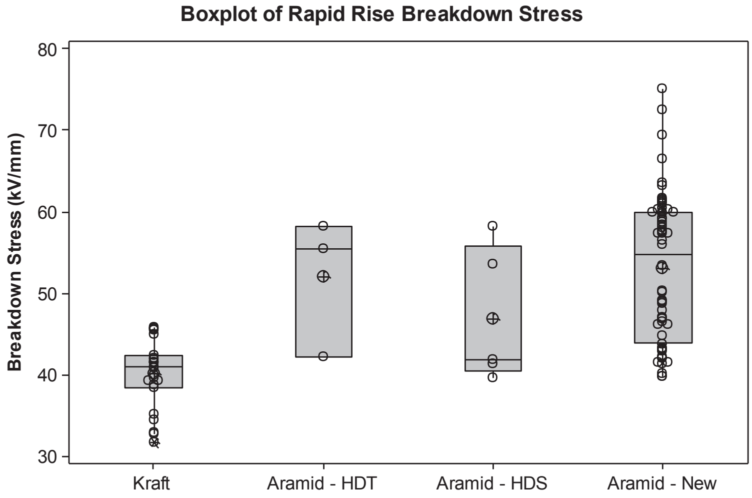

Figure 6 – Box Plot Comparing Rapid Rise Breakdown

Comparing the impulse breakdown stress of these same four products from Table XII indicates the new aramid paper is essentially equivalent to the high-density textured aramid. Both of these products are slightly better than the high-density smooth surfaced aramid paper. While all three aramid products show an improvement over the averaged five kraft products. The comparison is shown in Figure 7. In this series, the impulse ratio of the aramid papers is a bit higher than that of the kraft by about ten percent, but closer to the generally assumed value of 2,4.

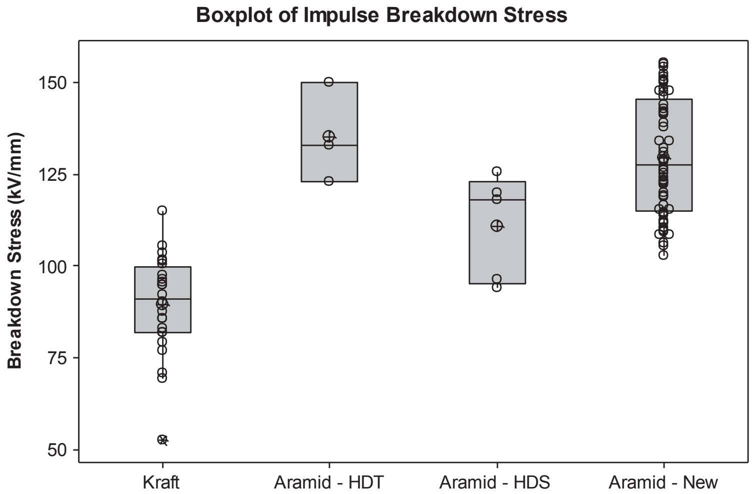

Figure 7 – Box Plot Comparing Impulse Breakdown

3. CONCLUSION

A number of conclusions may be drawn from this test program. For the layer type insulation, the three aramid families, differentiated by density and surface texture show a clear permittivity advantage, with values closer to the dielectric mediums of mineral oil or synthetic ester, compared to kraft paper. This advantage carries through to the wire insulation as well, again due partially to the lower density compared to the kraft paper. Contrary to conventional expectation, the medium density aramid papers compared very favorably in breakdown stress to the more widely used smooth surfaced, high-density products. However, the textured surfaced high-density aramid performed better than both of the other two aramid products.

The wire wrap insulation breakdown stress comparisons included impulse testing as well as rapid rise tests and the results were similar to the layer insulation comparisons. While there was little difference in the rapid rise test results, there was a noticeable improvement of the aramid papers compared to the kraft papers for impulse breakdown stress. Again, under impulse conditions, the textured surfaced aramid paper performed better than the other tested aramid and kraft papers. This testing also confirmed that the impulse ratio for the aramid products is similar to that of the kraft papers.

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