A COMPARISON OF FABRIC ARC RATINGS AND THE PERFORMANCE OF ARC RATED CLOTHING EXPOSED TO ARC FLASHES GENERATED USING AC AND DC ENERGY SOURCES

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Abstract – The predominance of DC energy sources (e.g. electric vehicles, photovoltaic power generation, uninterruptable power systems, etc.) is growing rapidly throughout the world. As such, workers in a variety of industries are being faced with a growing risk of exposure to arc flashes generated from these DC sources. However, all Standard Test Methods for determining arc ratings of products are based solely on AC energy, leaving a large unknown in the protective properties of all types of arc-rated clothing. In this paper, the arc ratings of various fabrics are identified and compared using both traditional AC open air arc rating methodologies and novel DC testing methodologies. Further, various commercially available arc rated garments were exposed to both AC and DC arcs to study the differences of full garment response to the two types of arcs. With a clearer understanding of the different reaction and protective performance values, best practices and updates to various international standards are proposed to ensure worker safety when dealing with the rapidly growing risk of arc flashes from DC energy sources. The arcs used in this study were open air, vertical electrode arcs. Other arcing techniques including box arc, ejected arc, and other electrode configurations were not employed in this study.

Index Terms — Arc Flash, Arc Rating, AC Energy, DC Energy, DC Arc Flash, ATPV, Arc Rated, ASTM F1959, IEC 61482.

I. INTRODUCTION

Protective clothing for electrical workers has been subject to standardized testing to determine its arc rating for twenty-five years, since the first edition of ASTM F1959 was published in 1999 [1]. Several subsequent revisions to that standard, along with the release of its European counterpart, IEC 61482-1-1 [2], have all been based in the same theoretical approach to arc ratings. Likewise, Standards for evaluation of various other types of arc rated PPE (e.g. Gloves, Face Protection, Fall Protection, and full garment evaluations) have all been based in the same theoretical approach to arc ratings. That approach has been to expose products, or the materials of their construction, to an electric arc generated using an AC power source.

Many entities rely heavily on accurate Arc Ratings in PPE for a variety of reasons. Fabric and Garment Manufacturers rely on accurate Arc Ratings to properly label their products. Those product labels convey critical information about protective properties of the fabric or garment and are imperative for product liability. Employers rely on accurate Arc Ratings to ensure that they are complying with relevant local, state, and federal requirements for providing their employees with proper PPE to match the incident energy for their equipment [3]. And, perhaps most importantly, end-users, the wearers of Arc Rated (AR) clothing, rely intimately on the accuracy of the Arc Rating on their garment label to ensure they return home safely after each day on the job.

With so many entities relying on the accuracy of the arc rating in a product label, it is imperative that the labeled arc rating represent the true protective properties of the garment. Today, every arc rating listed on an Arc Rated PPE label, worldwide, was established using AC energy. That leaves PPE manufacturers, employers, and end users uninformed about protection if exposed to DC arcs. This study aims to explore any differences between arc ratings generated using standard AC sources to those generated using DC sources. This first phase study only aims to explore and report any differences found. The intent is to educate both PPE manufacturers and end users about similarities or differences in order to increase awareness about protective properties of arc rated PPE when there is a potential for exposure to DC arc flash hazards.

II. SHIFT FROM AC TO DC

The shift from alternating current (AC) to direct current (DC) energy reflects a broader transformation in how we generate, distribute, and consume electricity. The shift is driven by both technological advancements and energy needs. Historically, AC has been the dominant form of electricity for power distribution due to its ability to travel long distances efficiently, facilitated by transformers that can easily step voltage levels up or down. However, the rise of renewable energy sources, particularly solar power, has highlighted the advantages of DC [4]. Solar panels generate electricity in DC form and converting it to AC for grid use introduces inefficiencies and energy losses.

Moreover, the increasing prevalence of energy storage systems, like batteries, which inherently operate on DC, further supports the case for a transition to more widespread use of DC power sources. As electric vehicles (EVs) gain popularity, their reliance on DC for charging and operation underscores a growing demand for DC infrastructure. Innovations in DC technology, including the development of DC microgrids, promise to enhance energy efficiencies, reduce transmission losses, and simplify the integration of various renewable energy sources [4]. The push for a cleaner, more efficient landscape has sparked interest in reevaluating our current power distribution frameworks, highlighting the potential for DC to play a crucial role in a sustainable energy future [5].

III. MATERIALS AND METHODS

Five different woven arc rated fabrics were selected for study and genericized as Fabric A through Fabric E for identification purposes. Fabrics A and B are comprised of a multi-fiber flame-resistant blend. Fabrics C and D are FR-treated cotton or cotton-rich fabrics; and Fabric E is a tri-laminate fabric, as shown in Table I. All selected fabrics were Navy in color.

These fabrics were deliberately selected based on overall market significance, while still providing a range of fiber content and construction. Fabrics were selected based on an anticipated arc rating of at least 8 calories. Fabric E was specifically selected to provide a single-layer fabric option with significantly higher arc ratings. In previous (unpublished) work by the authors, where subtle differences were found at the lower arc ratings, those differences were exacerbated in fabrics with higher arc ratings.

All samples of each fabric were taken from a single roll, so as to eliminate roll-to-roll or lot-to-lot variation as a factor in the study.

TABLE I

Products Selected for Testing

Sample ID	Composition	Nominal Weight (oz/yd^2)	Fabric Construction
Fabric A	Multi-Fiber FR blend	5.3	Twill
Fabric B	Multi-Fiber FR blend	6.1	Ripstop
Fabric C	Cotton/Nylon Blend	7.0	Twill
Fabric D	Cotton	9.0	Twill
Fabric E	Polyester/ePTFE	9.0	Trilaminate

AC arc testing was carried out precisely as prescribed in ASTM F1959/F1959M-24b. DC arc testing was carried out in a similar fashion, using ASTM F1959 apparatus, but modified to include a DC energy source. All specimens were tested in a single layer.

The Standard test method for determining the arc thermal protective rating of a fabric system requires a test fixture and instrumented (calorimeters) panels. In such test, the AC power source (50 or 60Hz) is sufficiently high voltage (approx. 2 kV) with a series reactive impedance to provide a stable arcing current of 8000A RMS. Based on the panel distance of 305 mm from the arc, the resultant heat flux on the fabric is approximately 45 cal/cm^2s.

For this project, the AC source was replaced with a DC source of equal capacity. This was achieved by using a standard diode three-phase (6 pulse) full-wave bridge rectifier. The use of a three-phase bridge rectifier provides a stable DC voltage and current with less than 5% ripple without additional filtering. The R_{limit} resistor was adjusted to provide nominal 8000A DC arcing current to maintain the same heat flux as with the AC circuit. A simplified circuit diagram is shown in Fig 1.

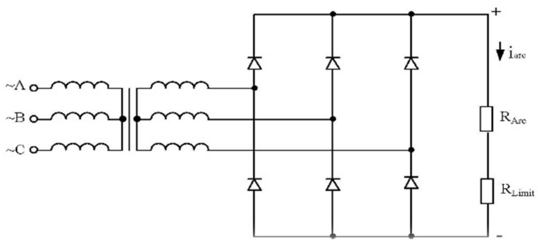

Fig 1: Three-phase full-wave rectifier

As prescribed in ASTM F1959 [1], all samples were washed three times and dried once using AATCC Laboratory Procedure 1, with wash procedure 3, temperature IV, drying procedure Aiii prior to cutting test specimens.

A variety of testing decisions were informed by knowledge of previously published variability in arc ratings [6]. To reduce the impact of variability on our conclusions, each fabric was tested six times – three times standard AC and three times experimental DC – for its arc rating. Testing was carried out over 6 consecutive testing dates in a manner such that no other testing was performed on the apparatus during the course of the study.

The six-day study was broken generally into three “DC days” and three “AC days”. The days were roughly alternated between AC and DC testing dates so that subtle trends in panel conditions or other environmental factors did not confound results for or against either AC or DC testing at the beginning or end of study. DC arc rating tests were carried out on days 1, 4, & 5 and AC arc rating tests were carried out on days 2, 3, & 6. There was a minor technical issue in the lab, unrelated to the study, which limited the number of tests carried out on Day 5. As such, only three of the five DC tests for Day-5 were completed that day. The remaining two tests were completed at the beginning of Test Day 6 before switching to AC to conclude the study.

Additionally, a limited set of commercially available arc-rated garments were exposed to DC arcs to compare the performance of other garment components beyond the fabric arc rating. These garments were placed on non-instrumented manikins, and evaluations were limited solely to qualitative visual assessments.

IV. RESULTS

The individual AC arc ratings and DC arc ratings of each fabric is shown in Table II. The average AC and DC ratings of each fabric is shown in Table III, along with a relative comparison between AC and DC arc ratings.

TABLE II

Individual Arc Ratings (AC and DC)

	AC Arc Ratings			DC Arc Ratings		
Sample ID	Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Fabric A	10.4	10.4	11.0	11.1	10.8	11.1
Fabric B	10.6	11.4	11.4	9.9	11.7	11.4
Fabric C	9.5	9.8	9.6	9.1	9.8	10.2
Fabric D	11.7	11.9	11.4	11.5	11.1	12.3
Fabric E	32.0	32.2	33.1	34.0	33.0	33.0

TABLE III

Average Arc Ratings (AC and DC), and Relative Comparison

Sample ID	AC Arc Rating	DC Arc Rating	Difference
Fabric A	10.6 (11)	11.0 (11)	+0.4 (0)
Fabric B	11.1 (11)	11.0 (11)	-0.1 (0)
Fabric C	9.6	9.7	+0.1
Fabric D	11.7 (12)	11.6 (12)	-0.1 (0)
Fabric E	32.4 (32)	33.3 (33)	+0.9 (+1)

Although all the results shown in Table III provide precision to the nearest 0.1 cal/cm^2 for comparison, the numbers in parentheses indicate the reported arc rating according to ASTM F1959, which requires results above 10 to be rounded to the nearest whole number. This comparison further solidifies the relative similarity of AC arc ratings to DC arc ratings, for this set of fabrics.

Fig 2 illustrates these values, and the relative difference between AC and DC arc ratings for all fabrics.

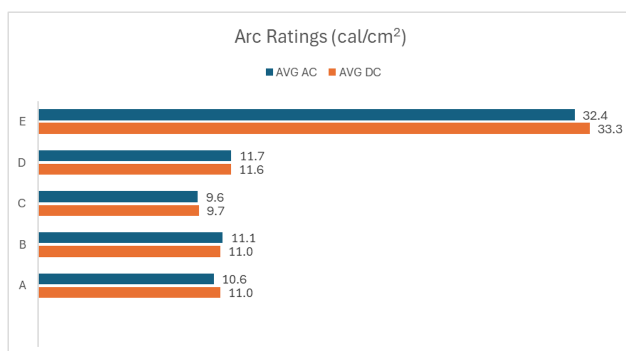

Fig 2. Average arc rating comparison of AC and DC for Fabrics A-E

Overall, the results show effectively no difference between AC and DC arc ratings for the fabrics studied.

The limited garment testing further supports the findings that arc ratings are unchanged when exposed to AC or DC energy sources. There was no notable difference in the qualitative observations made on garments or their components of construction (fabrics, seams/sewing thread, closures, trim and findings, etc.). Fig 3 shows a daily wear garment configuration before and after exposure to a DC arc flash. Response to the arc was identical to that experienced in a standard AC arc flash.

Fig 3. Example Arc-Rated daily wear before and after exposure to DC Arc Flash

V. DISCUSSION

The data very clearly suggests that there is no appreciable difference between arc ratings generated using AC energy and those generated using DC energy with this electrode configuration.

Previous studies have shown it to be very common to see double-digit percent variation in arc ratings over a series of months or years, and from lot-to-lot [6]. As such, it was important for this study to eliminate as many variables as possible, keeping all else equal when switching from AC to DC power supply.

Studying each fabric individually, we confirm that our efforts to reduce inherent variability were successful. There was no clear trend of an arc rating (either AC or DC) of a given increasing or decreasing consistently over successive testing dates.

When comparing the ASTM F1959 reported arc ratings (parenthetic data in Table III), it is most evident that the variation between AC and DC is well within the anticipated variation of the test. Three of the five test fabrics (Fabric A, Fabric B, and Fabric D) averaged exactly the same reported arc rating. These three fabrics show very good precision and indicate precisely no difference in arc ratings generated using AC and DC energy sources.

Fig. 4, Fig. 5, and Fig. 6 depict comparisons between AC and DC arc ratings for Fabric A, Fabric B, and Fabric D, respectively. They illustrate the precision of each type of arc rating for these fabrics and the lack of discernible difference between their average AC and DC arc rating.

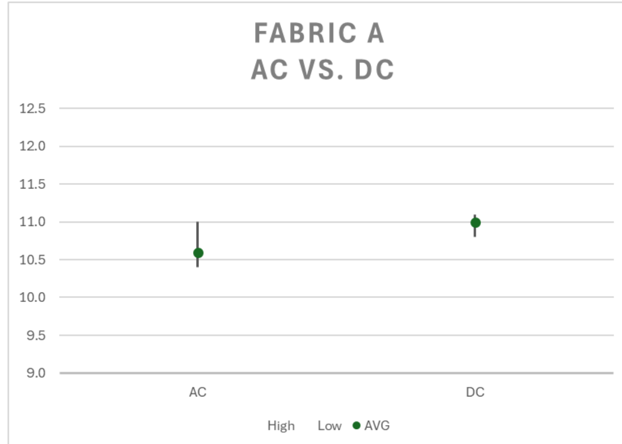

Fig. 4 Fabric A arc ratings, AC and DC, average and range

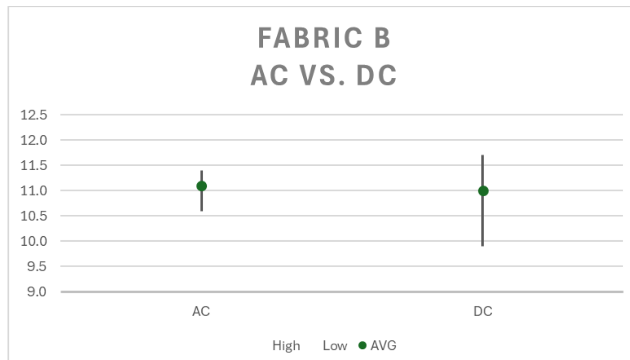

Fig 5. Fabric B arc ratings, AC and DC, average and range

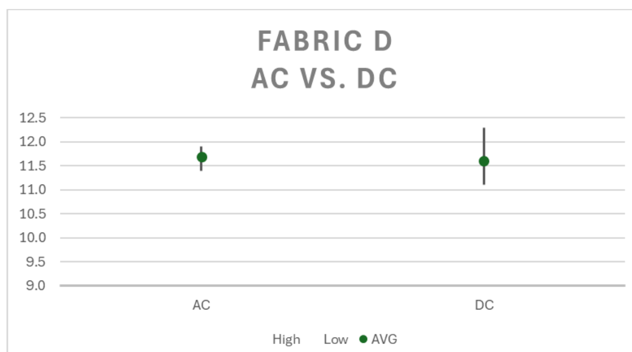

Fig. 6 Fabric D arc ratings, AC and DC, average and range

One of the five, and the only one reported with 0.1 cal/cm^2 precision because its value is below 10, (Fabric C) only showed a 0.1 cal/cm^2 difference. The comparison of AC to DC arc ratings for Fabric C is depicted in Fig. 7. At the relatively moderate arc rating of 9.6 or 9.7 cal/cm^2, a variation of 0.1 cal/cm^2 is well within the normal variation of the test and these results are considered effectively equal.

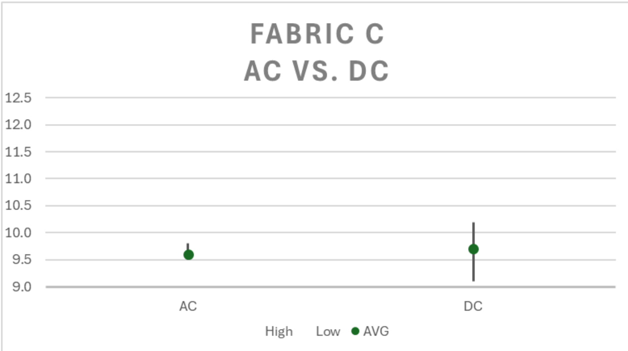

Fig. 7 Fabric C arc ratings, AC and DC, average and range

One of the five (Fabric D) showed a 1 cal/cm^2 difference. While the 1 cal/cm^2 difference is the largest absolute difference of the study, it was not the largest relative difference. The comparison of AC to DC arc ratings for Fabric E is depicted in Fig. 8. At the relatively higher arc rating of 32 or 33 cal/cm^2, such a variation is well within the normal variation of the test and these results are considered effectively equal.

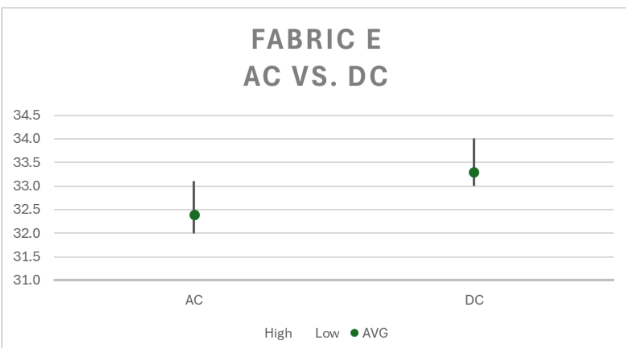

Fig. 8 Fabric E arc ratings, AC and DC, average and range

VI. CONCLUSIONS

Our research studied the relative arc ratings of fabrics when those ratings were determined using either AC energy or DC energy in order to shed light on an unknown area of mitigating risk with the use of arc rated clothing.

Results show that for single layer arc rated fabrics, at least the five fabrics evaluated in this study, there is no significant difference between arc ratings when exposed to AC arcs vs DC arcs. This is a rather encouraging start to what should become a more inclusive study but based on the initial findings, users of Arc Rated clothing can be reassured that the protection level cited in the garment label is representative of the expected performance in an arc exposure, regardless of the type of energy source, AC or DC.

While this testing was specifically carried out using ASTM F1959/F1959M-24B, the authors assume that resulting trends would mirror identically if calculated under IEC 61482-1-1.

Although repeating the multiple established variability studies conducted in the past was not an intended purpose of this study, our results also seem to indicate that arc ratings are no more or less variable when comparing ratings generated with AC versus DC arcs. In fact, the variation revealed by this study suggests that variability between arc ratings is markedly reduced when conducting multiple arc ratings on the same fabric in very rapid succession. Removing the variables associated with long spans of time (and presumably dozens of other tests) between two arc ratings on the same fabric appears to significantly reduce variation in arc ratings. This seems to indicate that much of the variability in arc ratings comes from non-fabric factors.

Based on the findings of this study, all stakeholders can be confident in the existing arc rating found on PPE labels, regardless of the energy source. Fabric makers and PPE manufacturers can confidently carry on labeling their products as tested according to ASTM F1959/F1959M or IEC 61482-1-1. Employers can feel confident in the protection they are providing their employees, assuming the PPE matches the arc flash hazard, regardless of whether that arc hazard is from an AC or DC energy source. And, most importantly, end-users can confidently wear arc rated clothing, knowing that the arc rating in the label applies to both AC and DC arc hazards.

VII. PATH FORWARD

While the results of this study are quite encouraging, it's important to understand that it was a very limited sample set. The authors recognize that the fabrics selected are all single-layer and all had ATPV results, as expected. It is unknown if or how the ratings would compare for multi-layer fabric systems or for systems that are prone to breakopen, such that the arc rating is EBT.

It is also important to recognize that the protective envelope is not limited to upper and lower torso protective garments. The full protective ensemble should be studied in a similar manner before the potential for differences in protection are dismissed. As such, the testing should be extended to other types of PPE before expanding conclusions beyond fabric arc ratings.

A similar study can be planned using ASTM F2675/F2675M for evaluation of arc ratings on hand protective products [7]. While the authors would anticipate similar results confirming minimal differences in arc ratings, we must recognize differences in the testing methodologies. ASTM F2675/F2675M evaluates specimens of whole hand protective devices, which may respond quite differently than flat fabric panels when exposed to thermal energy of an arc flash. Likewise, the materials of construction for hand protective devices (often leather or coated textiles) can differ significantly from fabrics evaluated in this study.

Perhaps more importantly, it will be critical to perform a similar study on face protection products according to ASTM F2178/F2178M [8]. Face protection products rely heavily on restriction of infrared radiation passing through the faceshield. If the spectral properties of a DC arc differ significantly from an AC arc, so too can the protective performance. As such, it will be important to carefully study the differences in arc ratings of face protective products when exposed to AC and DC arcs.

VIII. ACKNOWLEDGEMENTS

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IX. REFERENCES

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X. VITA

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Scott Margolin received his BS degree from the University of Delaware in 1992. He was in the fire service during college, spent 10 years at DuPont working with Kevlar and Nomex fibers, then was International Technical Director of Westex for 16 years, and has been Vice President of Corporate Strategy & Technical at Tyndale since 2016. He is an authoritative source for information on arc-rated and flame-resistant clothing and thermal hazard issues, chaired the Task Group responsible for ASTM F1959 for 7 years, and currently chairs the Partnership for Electrical Safety. He has conducted over 3000 flash fires and more than 3500 arc flashes at laboratories in the United States, Canada, South America, and Europe. He serves as a subject matter expert to organizations such as OSHA, NFPA, NJATC, ASSP, and NECA

James Cliver received his BS degree in Textile Chemistry from Clemson University in 1989. He subsequently joined Milliken and Company as a process improvement chemist in manufacturing, and later, moved into a research group at the Milliken Research Center. He then joined the Textile Division as a development engineer and was part of the technical team that developed some of the first FR and AR industrial fabrics for the division. Subsequent acquisitions also helped create the FR business under the Westex brand and he currently serves as the Global Certifications and Testing manager. He has been an IEEE member since 2009 and serves on the task group revising ASTM F1506 in addition to other ASTM and NFPA committees.

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Denise Statham received her BS in Textile Chemistry from the Georgia Institute of Technology in 1984 and an MBA from Georgia State University in 1991. She spent over 20 years in R&D and technical marketing roles with a flame-resistant fabric manufacturer and is a named inventor on 5 US Patents. She joined Bulwark Protection in a Business Development and Technical Services capacity. She currently serves as the Director of Technical Services for Workwear Outfitters. Denise is a longstanding member of various standards development organizations including ASTM, NFPA, and ANSI/ISEA. She currently serves as Chair of ASTM Subcommittee F23.80 on Flame and Thermal Hazards within Committee F23 on Personal Protective Clothing and Equipment.

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