COMPARISON OF METHODS FOR SELECTING PERSONAL PROTECTIVE EQUIPMENT FOR ARC FLASH HAZARDS

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Abstract – In 1960, a large global chemical company began documenting and implementing requirements for preventing injuries from electric arc flash hazards, including appropriate personal protective equipment (PPE). Methods evolved from requiring a 100% natural fiber long-sleeve shirt for a specific task to a detailed analysis with multiple flame-resistant clothing options. This paper compares the PPE required by these methods, based on hazards analysis in more than 65 manufacturing and laboratory facilities. The total costs for the example company are estimated for each method.

Index Terms — protective clothing, arc flash, electrical safety, electrical hazards.

I. INTRODUCTION

Over the past 30 years, there has been a growing interest in mitigating injuries from arc flash burns. Ralph Lee's paper "The Other Electrical Hazard: Electric Arc Blast Burns" [1] in 1982 was an early treatment of the subject. Using Lee's equations, an engineer could estimate the maximum incident energy on a worker's body due to an electrical arc flash.

Over the years, several generations of guidance emerged as an aid to determining the proper protective clothing to wear, based on system voltage, equipment type, and the task being performed. The development of empirically derived analysis techniques and "arc in a box" testing methods by Doughty, Neal and Floyd [2] more closely modeled arc flash incidents in industrial applications. The resulting hazard analysis method provided the basis for assessing incident energy exposures at common working distances, and for establishing more accurate ratings required PPE.

The effort to refine the methods for hazard assessment and protective clothing selection has continued, particularly through work associated with the National Fire Protection Association (NFPA) 70E [3] Technical Committee and the IEEE 1584 [4] Working Group.

II. DESCRIPTION OF METHODS

Since 1912, a large global chemical company has had a corporate standards program that now has more than 2000 engineering guidelines on design, procurement, installation, operation and maintenance of facilities and manufacturing processes. Approximately 400 of these guidelines are related to electrical technologies. The archives of these guidelines were researched to track the evolution in addressing electric arc flash hazards and the associated recommendations in personal protective clothing.

A. Upper Body Protection Method - Recognizing the Hazard

An indication that arc flash hazards required special attention was found in the 1960 initial publication of the corporate engineering guideline, "Electrical Safe Practices – General". Although there is no specific mention of the arc flash hazard, the guideline included a requirement that "workmen… should keep sleeves down and …avoid wearing unnecessary flammable clothing."

A more specific concern for arc flash hazards appeared in a 1970 revision of a guideline "Phasing Electrical Circuits" on procedures to verify correct phase matching on two separate power sources designed for closed circuit transfer. Although there was no mention of the arc flash hazard, the guideline required the use of "gloves, long sleeve shirt and a face mask". A 1971 revision changed the requirements to state "gloves, long sleeved cotton shirt, and a face shield to be worn over regular safety glasses." This revision also included a footnote that recommended use of a flame resistant aramid shirt "if available". A 1986 revision changed the requirements to "Use 36 inch long (10 oz/sq yd. aramid) switchman's coat and heat resistant face shield". This evolution indicates there was recognition that in an industrial power distribution system, the presence of two sources of power in one enclosure presented an electrical hazard different than electric shock and that bare skin could be burned and flammable clothing could be ignited.

A 1985 revision to "Electrical Safe Practices – General" mentioned the hazard of burns from electric arcs for the first time and added the requirement of 100% natural fiber long-sleeve shirt for all work in proximity to energized electrical equipment. The revision also included a suggestion that a flame-resistant jacket and hood be considered for any work associated with switchgear and motor control centers. A 1987 revision added the requirement that clothing of meltable manmade fibers must not be worn when working in the proximity of energized electrical equipment.

The Upper Body requirement for long sleeves of natural fiber provided protection up to the exposure level necessary for ignition of cotton. Generally for a lightweight cotton workshirt, the probability of ignition is less than 1% at approximately 3 cal/cm^2 [5]. Based on present day knowledge, this recommendation fell short because it did not reflect an understanding of the ignition behavior of non-flame-resistant cotton and did not consider the need for full body protection.

B. Multi-Layer PPE Method - Recognizing Hazards of Tasks and Equipment

The first comprehensive revision to the guideline "Electrical Safe Practices – General" was completed in 1990 and expanded its content by over 400%. Evidence of increasing understanding of the arc flash phenomena included:

- describing arc flash events as including blast hazards as well as thermal hazards
- describing an arc flash boundary
- recommending arc containment and arc directing switchgear designs
- application of current limiting fuses to reduce arc flash PPE requirements
- recognition that waist length switching coats do not prevent burns to the lower body

In 1993, another revision introduced the concept of differentiating arc flash PPE requirements dependent on type of equipment and to some extent the task being performed. For equipment protected by devices rated less than 200 amperes, long-sleeve natural fiber or flame-resistant (FR) garments were recommended. For equipment and tasks protected with devices above 200 amperes, a minimum of 6 oz/sq yd aramid full body protection was recommended. This corresponded to a protection level of approximately 6 cal/cm^2.

Safety procedures developed from these guidelines recommended two layers of 6 oz/sq yd aramid coveralls for tasks where the user judged that higher energy was present, such as in 480V switchgear. These two layers of aramid coveralls provided a protection level of approximately 20 cal/cm^2. Requirements for hood and heavy leather gloves were also included in these procedures.

This Multi-Layer PPE method improved arc flash protection for workers. However, based on present-day knowledge, it did not recognize hazards above the rating of two layers of FR clothing.

C. Detailed Analysis Method - Value for Engineering Studies

Learnings from arc flash incidents in the company's operations revealed variations in expected hazard severity and protective clothing performance. There were arc flash incidents in which injury severity was unacceptable, given that workers were in compliance with guidelines and procedures for PPE selection. In 1994 the company began conducting research to develop better methods to predict arc hazard severity and to establish performance ratings for arc flash PPE. The results of this research were shared with the technical community through IEEE conferences and publications [2][5][6].

In 1996, the guideline "Electrical Safe Practices – General" was revised to require arc flash analysis. This reflected a growing understanding that the arc flash hazard severity varied significantly with different equipment installations that physically appear very similar.

In 2000, three new engineering guidelines were published addressing arc flash hazard management, methods for performing detailed arc flash hazard analysis, and selection of personal protective equipment. In 2003, guideline "Electrical Safe Practices – General" was replaced with a corporate safety and health standard, "Electrical Safety Management". In the example company's culture, Engineering Guidelines are considered as non-mandatory recommended practices. Safety, Health & Environmental Standards have mandatory application to all company operations globally, including subsidiaries and joint ventures. This new standard established the requirement that engineering solutions to eliminate or reduce arc flash hazards, the selection of safe work practices, and the selection of arc flash PPE must be determined by engineering study and arc hazards analysis. The standard also established the requirement that compliance must be audited by a corporate second-party safety audit program.

The Detailed Analysis method used by the company is aligned with the analysis methods in NFPA 70E [3] and the IEEE 1584 Guide to Arc Flash Calculations [4].

III. ESTIMATING INJURY FREQUENCY

To establish a basis for estimating the number and frequency of electric arc burn injuries, the total number of OSHA recordable injuries, the total number of Lost Work Case injuries, and the number of arc flash incidents during the period 1997-2002 were reviewed. The number of arc flash incidents included those with injuries and those without injuries that would have likely resulted in serious injury if not for protective equipment worn.

An OSHA recordable injury is defined as any occupational injury or illness that involves one or more of the following:

- loss of consciousness
- restriction of work or motion
- transfer to another job
- medical treatment, beyond first aid.

A Lost Work Case is defined as an injury in which the injured person is unable to work on a subsequent scheduled shift because of a work-related injury.

During this period, the company recorded electric arc flash incidents that did result or would have resulted in an OSHA recordable and/or Lost Work Case injury. With this information, we established two electrical arc flash potential injury frequency factors. The first, **t**, is based on OSHA recordable injuries, and the second, **l**, is based on Lost Work Case injuries.

t = The number of arc flash incidents with potential for OSHA recordable injury, divided by the total number of OSHA recordable injuries = 0.0052

l = The number of arc flash incidents with potential for OSHA recordable injury, divided by the total number of Lost Work Case injuries = 0.03

For companies that do not have historical records of arc flash incident data, these factors may be useful in estimating arc flash incident and injury performance. They can be used in comparing options in designing an arc flash protection program. It should be recognized that the factors will differ from company to company, due to variations in safety and health record-keeping criteria, and overall safety performance. These factors can be applied to either actual injury numbers or injury frequency rates.

IV. COMPARING THE PPE REQUIREMENTS OF THE METHODS

A. Database used to compare methods

A diagram of a typical industrial electrical system in the company is shown in Figure 1. This includes one or more utility connections at high voltage, distribution at an intermediate voltage such as 12 kV, and utilization equipment at lower voltages such as 4.16 kV and 480V. Circuit breakers and fuses are used for protective devices.

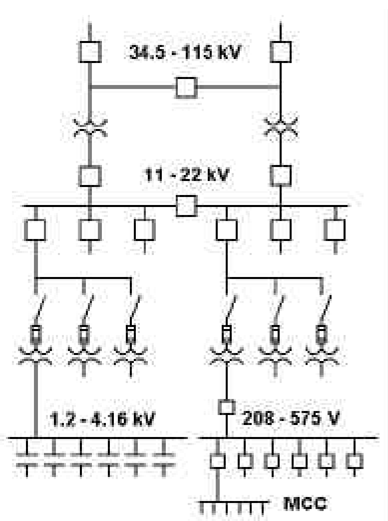

Figure 1 Typical Electrical System.

A summary of the arc flash hazard analysis results for this company was given as a recent paper by Doan and Sweigart [7]. Information on the equipment studied for the different voltage levels is shown in Table 1, including the minimum, median, and maximum of incident energy in cal/cm^2.

B. Comparison of the methods

The hazard analysis data for 9 660 pieces of equipment, or buses, and over 1 000 000 annual exposures was evaluated for incident energy, type of equipment, and type of work being done. It is possible to compare the results of the other methods to the results of detailed analysis, with the assumption that analysis is the most accurate method available for finding the true incident energy for any given exposure.

Figure 2 shows the number of buses where workers would be over- or under-protected when using the Upper-Body PPE method, based on a comparison with the results of the Detailed Analysis method. “Equal” means that the method recommended the same PPE required by Detailed Analysis. For approximately one third of the buses, workers were over-protected, but of particular concern is that at nearly one half of the buses, workers were under-protected.

Table 1 Summary Of Equipment Studied

Voltage Range	Number of buses	Incident Energy		
		Min	Median	Max
34.5 kV & Up	260	< 1	4	99
11 to 25 kV	1531	< 1	17	278
2 to 5 kV	977	< 1	2.4	106
< 1kV	6890	< 1	2.2	482

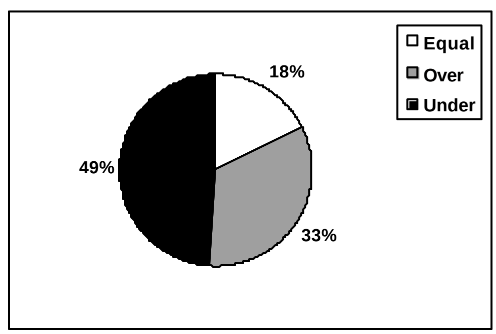

Figure 2 Proportion Of Equally-, Over- And Under-Protected Buses When Using Upper-Body Protection Method.

One way to more thoroughly understand this information is to consider the exposures that workers have with this equipment in the course of their work. For example, high-voltage (HV) equipment is operated less frequently than low-voltage (LV) motor control centers (MCCs). Table 2 is an estimate of the number of annual worker exposures for each piece of equipment, based on voltage level.

Table 2 Annual Exposures For Each Piece Of Equipment

Equipment	Annual Exposures
HV	2
Distribution	4
LV Switchgear	12
MCCs	365

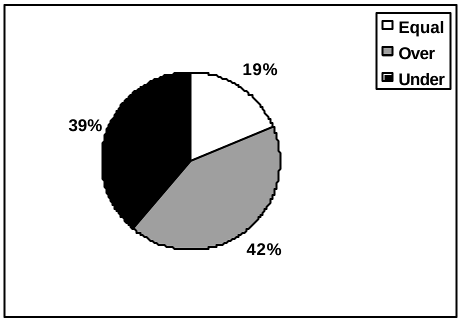

Figure 3 Proportion Of Equally-, Over-, And Under-Protected Exposures When Using Upper-Body Protection Method.

Figure 3 shows the proportion of annual exposures where workers were over-, under-, or properly-protected when using the Upper-Body PPE method, again based on a comparison with the Detailed Analysis. The concern is that for over one-third of the exposures, workers were thought protected by the method, but were actually using too little PPE.

Indeed, in 1999, the company had a multiple-injury incident where the workers were wearing too little PPE, but thought they were properly protected.

Figure 4 is a similar graph for the comparison between the Multi-Layer method and Detailed Analysis. On 27% of the buses, workers were under-protected, and were over-protected on 43%. This showed the improvement of using the Multi-Layer method in place of Upper-Body protection, since there was a significant reduction in under-protection.

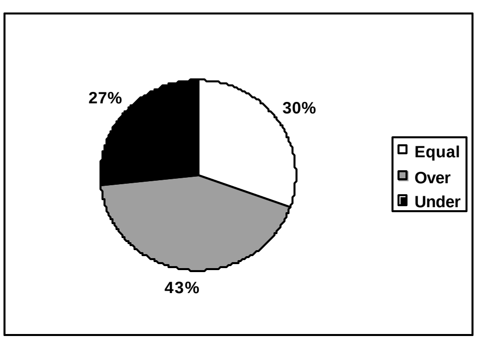

Figure 4 Proportion Of Equally-, Over- And Under-Protected Buses When Using Multi-Layer Method.

Figure 5 shows the exposure information for the Multi-Layer Method. Here, on 18% of the exposures, workers were under-protected, which also shows an improvement as compared to the Upper-Body Protection method.

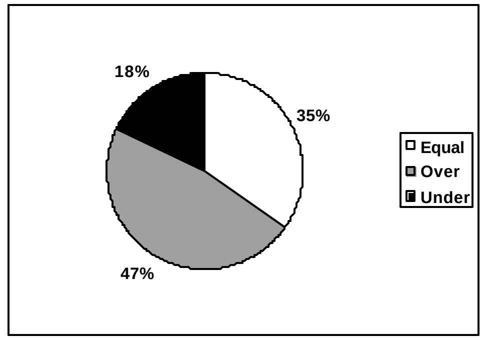

Figure 5 Proportion Of Equally-, Over- And Under-Protected Exposures When Using Multi-Layer Method.

Figures 2 through 5 indicate the substantial degree to which under-protection and over-protection would have resulted for one multi-site corporation. It is clear in this study that a significant degree of under-protection could have occurred. The consequences of these possible cases is that the worker, instead of receiving minimal burn injury, could receive second-and third-degree burns on the area of the body exposed to the arc flash.

The figures also indicate that for the potential exposures analyzed in this example, both methods would have led to over-protection in many of the cases. The primary issues with over-protection are worker discomfort and heat stress potential. Worker discomfort can quickly undermine PPE program acceptance and lead to inconsistent use of the specified PPE. Potential for heat stress can reduce worker effectiveness due to shortened work cycles and if not carefully monitored can lead to serious health consequences or fatalities. Finally, over-protection is costly in that more PPE is purchased than is actually needed.

The significant point to be made here is that the use of any simple method using task or equipment lists would miss the identification of high-energy arc flash hazards in some equipment, and lead to under-protection. It is tempting for a company to make the least expensive effort, and get it done quickly. The problem is there will probably be too much or too little PPE used on many of the tasks that are analyzed in that way. Detailed analysis is the best-known way to determine those points of high energy, and is the direction this company has moved in its electrical safety program.

V. COST COMPARISON OF THE METHODS

A. Estimated PPE Costs

The estimated cost range for protective clothing suitable for different levels of arc exposure is provided in Table 3. Hazard Classes 0 through 4 were first suggested by Neal, Bingham and Doughty in Table 7 of their paper on protective clothing guidelines [6]. Due to the variation in expected garment life for the various types of flame resistant fabrics used in the manufacture of protective FR work clothing for Hazard Classes 0, 1 and 2, the cost per use is also provided for these everyday protective clothing items. For the Class 2 face-shield and for Classes 3 and above, where arc-rated switching suits and hoods are often used, the garment life is generally several years. However the equipment life depends on the frequency of use, the task duration, and the number of workers using the garment.

An alternate clothing description for Class 3 is a two-layer system of FR coveralls and/or FR shirt-and-pants, similar to the Second level in the Multi-Layer PPE method described in Section II. Depending on the weight of the fabrics, a two-layer system can have a maximum exposure rating of 20 to 25 cal/cm^2.

Table 3 Cost Of Protective Clothing

Hazard Class (Exposure cal/cm^2)	Clothing Description	Initial Cost per Set US$	Wear Life* Years	Cost Per Day US$
0 (0-2)	Untreated Cotton Coverall or Shirt & Pants	30-40	1.5	0.40 to 0.53
1 (2-4)	FR Treated Cotton Coverall or Shirt & Pants	50-60	1.5	0.66 to 0.80
	FR Meta-Aramid Coverall or Shirt and Pants	80-110	4	0.40 to 0.55
2 (4-8)	FR Treated Cotton Coverall or Shirt & Pants	60-70	2	0.60 to 0.70
	FR Meta-Aramid Coverall or Shirt and Pants & cotton T-shirt	100-120	4	0.50 to 0.60
	Face Shield	30-50	-	-
3 (8-25)	Arc Rated Switching suit and hood	400-600	-	-
4 (25-40)	Arc Rated Switching suit and hood	600-900	-	-
>4 (40-100)	Arc Rated Switching suit and hood	800-1100	-	-

***** Wear life estimates are based on one laundering and one wearing per week per garment.

In the company's studies, the proportion of PPE types required by the Multi-Layer method is shown in Table 4. The proportion of PPE types required by the Detailed Analysis method is shown in Table 5.

Table 4 Proportion Of PPE Required By Multi-Layer Method

PPE	Buses	Exposures
Single-layer (6 cal/cm^2 rating)	63%	98%
Two-layer (20 cal/cm^2 rating)	37%	2%

Table 5 Proportion Of PPE Required By Detailed Analysis

PPE Class	Buses	Exposures
0 (0 to 2 cal/cm^2 rating)	34%	43%
1 (2 to 5 cal/cm^2 rating)	32%	36%
2 (5 to 10 cal/cm^2 rating)	16%	14%
3 (10 to 20 cal/cm^2 rating)	9%	5%
4 (20 to 40 cal/cm^2 rating)	6%	1%
>4 (over 40 cal/cm^2 rating)	2%	1%

The estimated 5-year PPE cost for a typical site with 10 000 buses and 1 000 000 exposures per year can now be calculated as shown in Table 6. The costs of Classes 1 and 2 are calculated per exposure, and the costs of Classes 3 and above are per bus. The cost per bus is based on the estimate that a large 1 000-bus site might have one set of Class 3, 4, or 5 clothing for every 10 buses.

PPE costs for Classes 1 and 2 must be multiplied by 5 to cover the 5-year period. Also, Class 1 and 2 costs can be multiplied by 0.5 to show that workers would average two exposures during the typical workday.

The PPE costs for the company's Upper Body Protection method is zero, since only natural fiber clothing was required and was provided by the worker, not by the company.

Table 6 Estimated PPE Cost For The Example Company

Class	Multi-Layer		Detailed Analysis	
	Exp %	Cost, US$1 000	Exp %	Cost, US$1 000
1	98	1 348	36	495
2	0	0	14	210
	Buses %		Buses %	
3	37	222	9	54
4	0	0	6	54
>4	0	0	2	22
Total		1 570		835

For the first entry in Table 6, Class 1 for the Multi-Layer method, 98% of the exposures are Class 1 (reference the single layer entry in Table 4). Therefore, the cost for Class 1 in that method is:

1 000 000 exposures x 98% x 0.55 US$/exposure

x 5 years x 0.5 = US$1 347 500

For the entry in Class 1 under Detailed Analysis, the cost is:

1 000 000 exposures x 36% x 0.55 US$/exposure

x 5 years x 0.5 = US$495 000.

For the entry in Class 3 under Multi-Layer method, the calculation is:

10 000 buses x 37% x US$600/suit / 10 buses/suit

= US$220 000

The cost of Class 0 cotton clothing is not included in these estimates.

B. Estimated Costs of Engineering Analysis

The analysis required for implementation of each method is of a different complexity. The Upper Body Protection method was a simple decision based on voltage, and could be completed in a few days for a large site. The Multi-Layer method takes more effort, in reviewing equipment, tasks and understanding the hazards. The Detailed Analysis requires considerable study, short circuit analysis, and spreadsheet calculations. Previous studies have shown that a typical 100-bus site can take 4 weeks for a knowledgeable engineer to complete a detailed study. Table 7 shows an estimate of the costs of analysis for the methods.

Table 7 Estimated Costs Of Analysis

Method	Cost, US$/bus
No Arc Flash PPE	0
Upper Body Protection	5
Multi-Layer PPE	10
Detailed Analysis	200

C. Cost of Injuries

Burn injuries typically lead to one day in the hospital for each per cent of body area burn injury at a second-or third-degree level. The cost of treatment in a burn center ranges from US$10 000 to US$15 000 000 depending on the patient's status and complications. These high costs are discussed in and supported by an EPRI study published by the New York Academy of Sciences [8]. Electrical burn injuries may complicate and extend treatment time, and extensive burns at third-degree or 4th degree levels require prolonged, successive hospitalization and rehabilitation. Specific treatment cost for three electric arc flash burn injury cases is provided in Table 8.

The personal cost for an employee cannot be fully reflected by the cost data in Table 8. These injuries can include extremely serious burns, which result when flammable clothing ignites during an arc accident. Frequently, in the process of prolonged treatment and rehabilitation, the employee will not be able to return to work, will become depressed and his or her personal and family relationships will be negatively impacted.

The full cost for a company in the situations described in Table 8 can be several times the cost of treatment and rehabilitation for the injured employee. This is due to the need to investigate the accident, modify work practices, retrain employees, replace employees who are unable to return to work, establish a protective clothing program on an accelerated basis and upgrade electrical equipment and circuit protection devices. An estimate of the treatment and rehabilitation cost of an injury depending on the level of under-protection of the PPE is described in Table 9.

It is important to note that this analysis only covers the thermal hazard of the arc flash. There are other hazards associated with arc flash incidents such as hearing and vision injury and blast trauma that have been discussed in other research by Capelli-Schellpfeffer [9]. Additional research is needed to more fully understand the entire injury that can result from an electrical arc flash.

Table 8 Total Cost Of Burn Injury

Date of Accident & Clothing Type	Type of Cost	Cost US$	Personal Cost for Injured Employee
July 1993 Cotton Uniform	Medical Indemnity Vocational Total	813 000 774 000 10 000 1,597 000	Unable to return to work; quality of life lost
July 1994 Cotton Uniform	Medical Indemnity Vocational Total	310 000 49 000 10 000 369 000	Unable to return to work; quality of life lost
June 1995 FR Pants Cotton T-shirt FR Coverall	Medical Indemnity Vocational Total	37 000 6 000 2 000 45 000	Returned to work after a few weeks; quality of life preserved

Table 9 Estimated Costs Per Injury

PPE Specified by Method *	Description of Injury	Cost of Injury US$
Up to 6 cal/cm² low	Minimal stay of a few days in a burn center.	50 000
6 – 20 cal/cm² low	Longer stay in a burn center.	100 000
More than 20 cal/cm² low	third-degree burns; limited skin grafts.	200 000
No FR clothing specified, but calculations show clothing ignition hazard	Potential for clothing ignition; extensive third-degree burns; skin grafting; limited rehabilitation.	400 000

***** Compared with PPE specified by Detailed Analysis method.

D. Comparison of Total Costs of the Methods

The costs itemized above can be combined to determine the total cost of using each of the methods for an example company with OSHA recordables of 2 000 per year, over a 5-year period, with 10 000 buses and 1 000 000 exposures annually.

The cost of injuries was estimated as described in Table 9. In the 'No Arc-Flash PPE' case, the estimated injury cost would be OSHA recordables x # of years x **t** x cost of injury. This is 2 000 x 5 x 0.0052 x US$400 000; or US$20 800 000.

In the 'Upper-Body Protection' case, the estimated injury cost would be based on the proportion of exposures with under-protection, or 39%, from Figure 3. These are all clothing-ignition hazards, since the worker's lower body is not covered by FR garments. So the estimate is OSHA recordables x # of years x **t** x 39% x cost of injury. This is 2 000 x 5 x 0.0052 x 0.39 x US$400 000; or US$8 112 000.

In the 'Multi-Layer PPE' case, the estimated injury cost would be based on the composite proportion of exposures with under-protection that would lead to injuries according to Table 10. The result is OSHA recordables x # of years x **t** x composite estimated cost of injury. This is 2 000 x 5 x 0.0052 x US$118 500; or US$6 162 000.

Table 10 Proportion Of Under-Protection In Multi-Layer PPE Case

Under-protection	Proportion	Injury Cost	Composite Injury Cost
Up to 6 cal/cm²	39%	50 000	19 500
6 - 20 cal/cm²	23%	100 000	23 000
Over 20 cal/cm²	38%	200 000	76 000
Clothing Ignition	0%	400 000	0
Total			118 500

In the 'Detailed Analysis' case, the estimated injury cost would be based on the number of exposures with incident energy calculated above the heaviest FR garment (100 cal/cm²). In the referenced Detailed Analysis study [7], 0.7% of the exposures had incident energy above 100 cal/cm. So the result is OSHA recordables x # of years x **t** x 0.7% x estimated cost of injury. The largest estimated injury cost of US$400 000 should be used to show the serious nature if any injury were to occur at these high energy values. The result is 2 000 x 5 x 0.0052 x 0.007 x US$400 000; or US$145 600. This shows that there is approximately one third chance of an injury of this type in a 5-year period, based on the statistics of the example company's safety record.

The estimated costs of PPE, Analysis, and Injury can be combined to determine a comparative total for each method as shown in Table 11. This would be the total cost to an example company if only that method were used for a 5-year period.

Table 11 Total Cost To The Example Company

Method	PPE US$ 1000	Analysis US$ 1000	Injury US$ 1000	Total US$ 1000
No Arc Flash PPE	0	0	20 800	20 800
Upper-Body PPE	0	50	*8 100	8 150
Multi-Layer PPE	1 570	100	*6 150	7 820
Detailed Analysis	835	2 000	*150	2 985

*****Note: This is an ideal comparison in which all recommendations are followed. In practice, human error and other factors can increase injury frequency and increase overall costs when using any of these methods. These other factors include worker position and distance during the task, and proper operation of devices including fuses, circuit breakers, and electronic and electromechanical relays.

VI. CONCLUSIONS

This comparison of applying three different approaches in implementing an arc flash protective clothing program clearly shows that all three will save lives and reduce the severity of serious injury from arc flash burns. The methods do differ in initial and life cycle costs and in the up-front engineering and financial resources needed for hazard analysis. The detailed hazard analysis method is the best method known at this time to assure optimum match of protective clothing to hazard severity. The results from detailed analysis can also be used to compare system design options for reducing incident energy, to select tools and safe work practices to minimize personnel exposure, and to decide whether certain work can be safely performed on or near energized electrical equipment.

VII. ACKNOWLEDGEMENTS

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IX. VITA

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