Industrial Flash Fire and Burn Injury Fundamentals with an Instrumented Manikin Demonstration of Protective Clothing Performance

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Abstract

NFPA 2112 and 2113 are the first comprehensive North American standards to provide guidance on minimum material performance specifications for selection, care, use and maintenance of flame resistant clothing to protect workers against industrial flash fires. An instrumented manikin flash fire test specifying a limit on predicted body area burn injury is among the NFPA 2112 requirements. The level of body area burn injury is discussed as a key indicator for victim survival. The level of predicted body burn injury for various types of flame resistant clothing systems over a range of flash fire exposure levels is discussed. Basic guidelines for wearing flame resistant clothing are provided.

Introduction

Workers in the petroleum, petrochemical, chemical and related industries in North America have only recently gained the benefit of comprehensive standards to provide guidance on material performance, selection, use, care and maintenance of flame resistant clothing for protection against flash fire hazards. A new requirement regarding instrumented thermal manikin testing of flame resistant (FR) clothing provides an assessment of the protection level of fabrics used in FR clothing systems in terms of predicted body area burn injury. Body area burn injury is a key predictor of victim survival from a flash fire incident, and the protective performance of flame resistant clothing systems over a range of flash fire exposure levels can be used to match protective clothing systems to identified flash fire hazards. Following guidelines on garment wearing procedures can maximize the protection offered by the selected FR clothing system.

Flash Fire Hazards

Historically, flash fire hazards were viewed as fairly rare incidents from which workers in the affected area would attempt to escape to avoid lifethreatening injuries. In some cases, the presence of multiple exposure conditions in a flash fire incident, i.e., hazardous chemicals, toxic fumes and/or off gases has complicated protective clothing and equipment strategies. After a number of very serious incidents involving the ignition of conventional work clothing which resulted in multiple burn injury fatalities

fatalities and serious nonfatal burn injuries, the petroleum, petrochemical and chemical industries began to broadly adopt FR clothing in order to increase worker survival in the event of an industrial flash fire incident. Generally these adoptions involved the use of FR coveralls or FR shirts and FR pants by all employees and contractors exposed to flash fire hazards on a specific industrial site. This provided workers with a few extra seconds of escape time and resulted in reduced body area burn injury levels and increased the chance of surviving a flash fire incident. Table 1 provides typical exposure parameters for industrial flash fire hazards.

Table 1. Typical Industrial Flash Fire Exposure Parameters

HAZARD EXPOSURE FACTORS	TYPICAL RANGE
Total Exposure Energy, cal/cm^2	1 to 20
Percent Radiant Heat Energy	30 to50
Percent Convective Heat Energy	50 to 70
Heat Flux, cal/cm^{2}s	1 to 4
Potential Exposure Time, seconds	1 to 5
Concussive Forces	Variable
Presence of Smoke/Fumes	Yes
Mechanism for Recurrence	Re-ignition of Flammable Chemicals or Gases

Ignition of Conventional Clothing by Flash Fire Exposure

Conventional work clothing is typically made of 100% cotton fabrics or fabrics made of polyester/cotton fiber blends or nylon/cotton fiber blends. All of these fabric types are flammable, and in addition, the nylon and polyester fibers can melt onto the skin aggravating the burn injury. Polyester or nylon blend containing fabrics, due to their durability, are generally lighter in weight, i.e. lower fabric areal density, than 100% cotton fabrics. Lighter weight fabrics ignite at lower exposure energy and burn with a higher flame spread rate than heavier weight fabrics. Fabric weight is usually expressed in ounces per square yard. An exposure of approximately one cal/cm^2 per unit of fabric weight (when expressed in oz/yd^2) is usually required for fabric ignition, i.e. an exposure of approximately 6 cal/cm^2 will ignite a 6 oz/yd^2 cotton work shirt, but approximately 10 cal/cm^2 would be required to ignite a 10 oz/yd^2 coverall. Darker colors, due to a greater tendency to absorb radiant heat energy, tend to ignite at lower incident energy levels than lighter colors. The primary point on ignition is that all conventional work clothing fabrics can ignite, will continue to burn on the wearer's body and will cause more severe burn injury to greater areas of the body than the actual flash fire. If clothing is ignited, burn injury can quickly spread to areas of the body that were not initially exposed in the flash fire incident.

Burn Injuries from Flash Fire Hazards

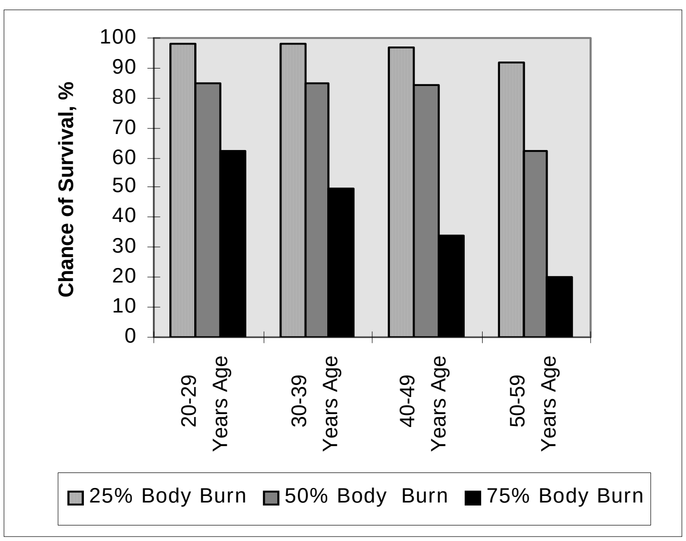
In spite of significant progress in reducing industrial fire hazards, thousands of second and third degree burn injury cases occur in the work place each year in North America (1). These injuries result from the exposure of workers to the intense radiant and convective energy resulting from a flash fire incident. Flash fire exposures are usually of sufficient intensity and duration to ignite conventional

conventional work clothing and burn unprotected (bare) skin. The most serious of these burn injuries including many of the fatalities involve the ignition of the victim's clothing during the flash fire exposure. The relatively long time, e.g. 30 to 60 seconds, of continued burning of conventional work clothing on the body after the initial flash fire has ceased significantly increases both the burn depth and the total body area suffering burn injury. The increase in body burn area has been shown to directly affect the survival rate of burn injury victims. The total area of body burn injury is a key survival factor for burn victims based on the 1991-1993 American Burn Association study (2) as shown in Figure 1. The chance of survival drops sharply as the body area burn increases to 75% for all four age groups that make up the work force demographics. It is interesting to note that burn injuries in the range of 75% of the body area can very readily result from ignition and the continued burning of flammable clothing on the victim's body.

It is important to note that conventional clothing fabrics made from natural fibers, polyester fibers, nylon fibers or blends of these fibers are all flammable and can ignite and continue to burn on the body. It has been reported that fabrics made of meltable fibers like polyester and nylon can lead to more serious burn injuries (3). Generally, polyester, nylon and blends of these meltable fibers with cotton are utilized in lighter weight fabrics which tend to ignite and burn more readily. However, conventional fabric, regardless of weight, can ignite in a flash fire and continue to burn on the body with potential to create life threatening burn injuries.

Flame-resistant (FR) clothing can significantly reduce burn injury resulting from flash fire exposure. This occurs first by minimizing or avoiding clothing ignition, and second by creating a thermal barrier, which reduces the exposure energy reaching the victim's skin. Consequently, over the past decade, there has been increased emphasis by OSHA, ASTM and NFPA standards organizations on the use of FR clothing by workers exposed to flash fire hazards.

Figure 1 - Chance of Survival from Burn Injury



Protective Clothing Standards for Flash Fire Hazards

Protective clothing standards for the flash fire hazard have been slow to emerge in North America.

The General Duty Clause from the Occupational Safety & Health Act of 1970, Section 5(a)(1) states that personal protective equipment should be suitable for the task performed. This provided the only guidance available until late 2000 when CGSB-155.20 *Workwear For Protection Against Hydrocarbon Flash Fire* and CGSB-155.21 *Recommended Practices for the Provision and Use of Workwear for Protection Against Hydrocarbon Flash Fire*, were issued by the Canadian General Standards Board. In 2001, the National Fire Protection Association (NFPA) issued NFPA 2112 *Standard on Flame Resistant Garments for Protection of Industrial Personnel Against Flash Fire*

Table 2. Key Flame Resistant Clothing Requirements for the NFPA 2112 Standard

PROTECTION FEATURE	STANDARD TEST METHODS	SPECIFIC REQUIREMENTS
Flammability for Fabric and Reflective Striping	ASTM D 6413 Vertical Flame Test	4 inch Max. Avg. Char Length 2 s Max. Avg. Afterflame No melt and drip Before and After 100 Launderings or Dry Cleanings
Blocking of Convective and Radiant Heat Energy Method 1	NFPA 2112 Spaced Thermal Protective Performance Test (TPP Spaced)	6 cal/cm^2 Minimum Avg. Before and After Three Launderings or Dry Cleanings
Blocking of Convective and Radiant Heat Energy Method 2	NFPA 2112 Contact Thermal Protective Performance Test (TPP Contact)	3 cal/cm^2 Minimum Avg. Before and After Three Launderings or Dry Cleanings
Body Area Burn Injury Protection	ASTM F 1930 Instrumented Manikin Test Standardized Coverall with Cotton T-Shirt and Briefs	50% Max. Avg. Body Area Burn Injury for a 2.0 cal/cm^2s Heat Flux for 3.0 seconds After One Laundering or Dry Cleaning
Thermal Shrinkage Resistance of Fabric	NFPA 2112 Forced Air Circulating Oven Test and AATCC 135 for Dimensional Measurements	10% Maximum Shrinkage for Oven Exposure of 5 minutes at 500^{o}F Before and After Three Launderings or Dry Cleanings
Heat Resistance of Fabrics, other Textile Materials and Reflective Striping (Excludes Labels)	NFPA 2112 Forced Air Circulating Oven Test	No Melting and Dripping, Separation, or Ignition for Oven Exposure of 5 minutes at 500^{o}F Before and After Three Launderings or Dry Cleanings
Hardware Buttons, Fasteners, Zippers, Closures, Etc.	NFPA 2112 Forced Air Circulating Oven Test	No Melting and Dripping, Separation, or Ignition for Oven Exposure of 5 minutes at 500^{o}F and Shall Remain Functional
Sewing Thread	Federal Test Method Standard	Inherently Flame Resistant

(Excludes Embroidery)	191A, Test Method 1534	No melting at 500^{o}F

Note: Labeling, Label Print Durability , and Design Requirements, as well as third party compliance verification are included.

and NFPA 2113 *Standard on Selection, Care, Use, and Maintenance of Flame Resistant Garments for Protection of Industrial Personnel Against Flash Fire.* The CGSB and NFPA standards are similar; however, the NFPA 2112 standard is more comprehensive in its requirements. In addition, NFPA 2112 is the first protective clothing standard worldwide to include a requirement that fabrics used in FR clothing systems be tested in a simulated flash fire exposure using an instrumented thermal manikin. A listing of the key NFPA 2112 requirements is shown in Table 2.

Flame Resistant (FR) Clothing

The primary benefit of Flame Resistant (FR) clothing is that it will self extinguish, usually within a few seconds after the ignition source is removed. Consequently FR clothing will not add to the burn injury by continuing to burn on the wearer's body like conventional work clothing will. In addition, FR clothing also provides a thermal barrier which can be designed as a single or multiple layer system to minimize burn injury to skin which is under the FR clothing. The NFPA 2112 "Spaced" and "Contact" Thermal Protective Performance (TPP) Test Methods are used to quantify the thermal insulative performance of single and multiple layers of flame resistant (FR) fabrics. These methods expose FR fabrics or systems to a controlled convective and radiant heat source. The resulting TPP values indicate the relative degree of insulative performance provided by the FR fabric or system. However, the TPP values do not provide a quantitative assessment regarding predicted burn injury (4).

One of the key benefits offered by the NFPA 2112 standard is inclusion of instrumented thermal manikin testing. This provides a quantitative assessment of the predicted body area burn injury for a specified exposure energy using a standard garment made of a specific FR fabric.

Instrumented Thermal Manikin Testing

Development of instrumented thermal manikin test procedures using flash fire exposures to assist in clothing flammability studies began in North America during the 1970's by the U.S. military and the DuPont Corporation (5, 6). Work is still in progress to refine thermal exposure control and uniformity, thermal sensor technology, and burn injury prediction models. There are currently three manikin systems operating in North America, four in Western Europe and two in Japan with several additional systems under development. The American Society for Testing and Materials method ASTM F1930 *Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Flash Fire Simulations Using an Instrumented Manikin* was established in 1999. As noted above it is among the required tests for the NFPA 2112 standard. The F1930 test method utilizes a flash fire exposure of controlled intensity and duration with an instrumented manikin with at least 100 thermal sensors and using a burn injury prediction model for human tissue. The predicted second and third degree body area burn injury is determined for specific garments tested on the manikin. The specific NFPA 2112 test conditions using F1930 require a 3.0 second flash fire exposure with a heat flux of 2.0 cal/cm^{2}s. The total exposure energy is 6.0 cal/cm^2. A standard pattern coverall made from the FR test fabric is evaluated using cotton T-shirt and briefs underneath. NFPA 2112 requires the flame resistant (FR) fabric material to have 50% or less predicted body area burn injury.

Use of a thermal manikin test is an important advance since it evaluates the ability of an FR fabric to shield the wearer from thermal energy when the FR fabric is in the form of a basic, properly fitted garment on a representative human form. This is an important distinction versus a bench top fabric test like the TPP. Table 3 shows the instrumented thermal manikin test results and predicted victim survival

Table 3. Instrumented Thermal Manikin Test Results and Survival Statistics for FR Systems

FR FABRIC OR SYSTEM OF FABRICS	3 SECOND EXPOSURE 6 cal/cm^2			4 SECOND EXPOSURE 8 cal/cm^2		
	% PREDICTED BODY AREA BURN INJURY	% PREDICTED VICTIM SURVIVAL		% PREDICTED BODY AREA BURN INJURY	% PREDICTED VICTIM SURVIVAL	
Nominal Fabric Weight		**Age 30 to 39**	**Age 40 to 49**		**Age 30 to 39**	**Age 40 to 49**
5.5 oz/yd^2 Untreated Cotton	96	15	13	96	15	13
4.5 oz/yd^2 Nomex®IIIA	38	95	88	52	83	72
6.0 oz/yd^2 Nomex®IIIA	29	97	94	44	91	82
7.5 oz/yd^2 Nomex®IIIA	19	98	97	37	96	89
5.5 oz/yd^2 Nomex® Comfortwear (Nomex®/Rayon 65/35 Blend)	--	--	--	47	89	79
6.5 oz/yd^2 Nomex® Comfortwear (Nomex®/Rayon 65/35 Blend)	--	--	--	38	95	88
9.0 oz/yd^2 Indura® Flame Retardant Treated Cotton	8	99	99	80	37	29
9.5 oz/yd^2 UltraSoft® Flame Retardant Treated Cotton/Nylon 88/12 Blend	9	99	99	82	33	28
6.0 oz/yd^2 Nomex®IIIA with cotton long johns	--	--	--	<25	98	96
6.0 oz/yd^2 Nomex®IIIA with FR Batting and FR Liner, i.e. Insulated Coverall	--	--	--	<15	99	99

Note: Tests performed according to ASTM F1930, Heat Flux is 2.0 cal/cm^{2}s, FR garments laundered prior to testing, FR coveralls used unless otherwise noted, cotton T-shirt and briefs under FR clothing. Each predicted body area burn injury result is the average of three individual tests.

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statistics for untreated cotton and various FR fabrics and FR fabric systems for three and four second flash fire exposures (6 cal/cm^2 and 8 cal/cm^2 total exposure levels). The high predicted body burn area and low predicted victim survival rate for untreated cotton is very apparent in Table 3. Inherently flame resistant lighter weight fabrics like Nomex®IIIA tend to exhibit higher body area burn injury at three second test exposures than heavier weight flame retardant treated products like Indura® and UltraSoft®. This impact of heavier fabric weight can also be observed with the three weights of Nomex®IIIA. However, this situation changes for a four second exposure due to the sharp rise in predicted body area burn injury exhibited by these flame retardant treated products. Table 3 shows that the significant increase in predicted burn injury at a four second exposure for treated products like Indura® and UltraSoft® is reflected in an equally significant decrease in the predicted survival rate for workers in age groups from 30 to 39 and 40 to 49 years. The decrease in the chance of survival for workers 50 to 59 years old would be even greater as indicated in Figure 1. Predicted survival for the lighter weight Nomex®IIIA and Nomex® Comfortwear products is maintained at a relatively high level for both three and four second exposures since these products exhibit a more gradual increase in predicted body area burn injury as the total exposure energy increases.

Table 3 also indicates potential protection strategies for higher exposure levels. For example, if long underwear is worn under a FR coverall, predicted survival for a four second exposure can be increased to over 95%. A similar increase in survivability can be achieved by wearing an insulated FR coverall which consists of several flame-resistant fabric layers. Multi-layer FR clothing systems can be designed to protect wearers against higher exposures when hazard analysis indicates the potential for higher exposure times, or high heat content fuels are involved.

The ASTM F1930 thermal manikin test method can also be extended beyond the minimum requirements of NFPA 2112 to assess the impact of many important FR clothing aspects such as naturally occurring air gaps between the garment and the manikin surface, garment fit, number, size and location of pockets, fabric type, fabric weight, fabric flame shrinkage, and exothermic reactions exhibited by flame retardant treated fabrics. Flash fire thermal manikin testing also enables analysis of various clothing systems such as the use of non-melting under garments, and FR and non-FR outerwear, e.g. wind breakers, cold weather gear and rainwear. Manikin test results can assist when designing multi-layer FR clothing systems to provide a high level of protection over the full range of expected flash fire exposures—beyond the NFPA 2112 minimum 6 cal/cm^2 exposure requirement.

Flash Fire Hazard Analysis

The new NFPA 2113 Standard requires that a hazard analysis be performed for the industrial work place. Exposure energy can be estimated for each flash fire hazard scenario by estimating the fire intensity(heat flux) and exposure time (escape time or incident duration). Flash fire incidents are unexpected and uncontrolled events that can occur over a broad range of exposure levels. Generally the heat flux would be estimated at 2 cal/cm^{2}s for most fuels, i.e. propane, natural gas, ethane, methane. If the hazard involves explosives or very high heat content chemicals, the heat flux estimate can be significantly higher and will depend on the specific fuels, the exposure geometry and other hazard parameters. The exposure time is based on escape time from the flash fire or the estimated fire duration based on available fuel and oxygen. The total exposure is the product of the heat flux and the exposure time. For example, the heat flux for a high heat content fuel could be estimated at 3 cal/cm^{2}s and the expected exposure time could be estimated at 3 seconds yielding a total exposure of 9 cal/cm^2. For a propane gas cloud, the heat flux could be estimated at 2 cal/cm^{2}s and the escape time for this large flash fire area could be estimated at 4 second yielding a total exposure of 8 cal/cm^2. The work tasks and locations of an industrial worker may involve a range of flash fire exposure hazards, and consequently a comprehensive task-by-task analysis must be done. This hazard analysis will provide the predicted exposure threat required to determine when a single layer FR clothing system will provide adequate protection and when a multi-layer FR clothing system will be needed. Therefore, if the estimated exposure energy is significantly greater than the specified NFPA 2112 minimum requirement of 6 cal/cm^2, then a multi-layer FR clothing system and/or modified work practices may be required to minimize burn injuries.

Flash fire instrumented manikin testing according to the ASTM F1930 method has enabled many companies to address specific flash fire hazards more quantitatively. FR clothing systems can be tested over the range of potential flash fire exposures identified in a hazard analysis. This will facilitate selection of a FR clothing system designed to match the exposure energy levels identified during the hazard analysis. This will permit FR clothing systems to be selected to minimize predicted body area burn injury for the probable worst case hazard scenario. When body area burn injury is minimized, victim survival is expected to be maintained at a high level. In addition, pain and suffering is reduced and preservation of the victim's quality of life is significantly increased.

Guidelines for Wearing FR Clothing

The following guidelines provide information on ways to maximize the protection offered by FR clothing.

- Protective Clothing Selection Must Be Based on the Probable Worst Case Exposure for a Task

- Flame-Resistant Clothing Should Provide a Good Functional Fit for Protection and Comfort
- Loose Fitting Clothing Provides Additional Thermal Protection Due to Increased Air Spaces
- Sleeves Cuffs Should be Full Extended and Secured
- All Garments Including Outerwear Should Be Fully Fastened Closed
- Clothing Should Be Free of Flammable Contaminants Which Can Ignite and Increase Burn Injury
- Appropriate Protective Neck, Face, Eye, Head, Hand, and Foot Coverings Should Be Worn
- Outerwear Must be Flame Resistant since Flammable Outerwear Can Ignite and Continue to Burn Essentially Eliminating the Protection of Flame Resistant Clothing Worn Underneath
- Undergarments Worn Against the Skin Should Be Non-Melting Since Meltable Undergarments Can Increase Burn Injury Severity
- Non-Melting Undergarments Made of Cotton, Wool, Silk, Rayon, or FR Fabrics Can Be Worn Under FR Clothing to Increase Thermal Insulation and Protection from Flash Fire Exposures

Conclusion

New standards will assist in providing industrial workers with protective FR clothing systems which are designed to minimize burn injury and maintain high burn victim survival rates. It is important to estimate the expected flash fire threats using workplace hazard analysis. It is also important to assess FR clothing systems over a range of exposure levels, beyond the NFPA 2112 minimum requirement since some types of FR clothing exhibit sharp increases in body area burn injury for modest increases in exposure level. This is critical since flash fire incidents are uncontrolled events which can occur over a broad range of exposure levels. FR clothing systems can be designed to minimize body area burn injury over a broad range of exposure levels. When body area burn injury is reduced, the survival rate for burn victims is significantly increased, and the ability to preserve the victims' quality of life can be greatly enhanced.

References

1. Suruda, A., and D. Wallace. 1996. Fatal work-related injuries in the US chemical industry. *Journal of Occupational & Environmental Health*. 68 (6):425-428.

2. Saffle, J.R., Davis, B., Williams, P., & The American Burn Assoc. Registry Participant Group, Recent Outcomes in the Treatment of Burn Injury in the United States: A Report From the American Burn Association Patient Registry, *Journal of Burn Care & Rehabilitation*, Vol. 14, No. 3, Part 1, May/June 1995.

3. Hull, D., Grindlinger, G.A., Hirsch, E.F., Petrone, S., Burke, J., The Clinical Consequences of an Industrial Aerosol Plant Explosion, *Journal of Trauma*, Vol. 25, No. 4, 1985

4. Stoll, A. M. & M. A. Chianta, Heat Transfer Through Fabrics as Related to Thermal Injury, *Transactions New York Academy of Sciences*, No. 33, 1971

5. Behnke, W.P., Predicting Flash Fire Protection of Clothing from Laboratory Tests Using Second-degree Burn to Rate Performance, *Fire and Materials*, Vol. 8, No. 2, 1984

6. Norton, M.J.T., Kadolph, S.J., Johnson, R.F., Jordan, K.A., Design, Construction, and Use of Minnesota Woman, A Thermally Instrumented Mannequin, *Textile Research Journal*, Vol. 55, No. 1, January, 1985