

Summary

The International Symposium on the Performance of Protective Clothing, on which this publication is based, may have been the most important forum on protective clothing in recent years. Its purpose was to bring together, for the first time, all those interested in protective clothing for occupational exposures, to present the findings of relevant research and, perhaps most important, to stimulate discussion and further development efforts.

The response to the symposium was overwhelming, not only in the numbers of participants and diversity of interests but also in the expertise of the authors. Further symposia are planned.

The papers in this volume are organized into sections by topic area. The sections are arranged to distinguish between chemical protection, thermal protection, and other related topics that are generally important to the performance of protective clothing.

Summaries of the papers follow.

Permeation Resistance of Chemical Protective Clothing Materials

Test Methodology

Davis, Feigley, and Dwiggins set the tone for technical discussions on permeation test methods by reviewing the performance of glove materials challenged by liquified coal. In carrying out their work, these authors compared performance measured by a test method using flame ionization detection with performance measured by a test method using radio-labeled, single-species detection. The data show that test methods that do not specifically quantify the compounds of toxicological significance can provide misleading information on the degree of protection provided. A method responding to all volatile components of a mixture may yield results that differ substantially from results of a method responding to a single substance only.

Perkins and Ridge studied the utility of infrared spectroscopy as the detection methodology in the ASTM Test for Resistance of Protective Clothing Materials to Permeation by Hazardous Liquid Chemicals (F 739-81). The authors concluded that infrared (IR) detection provides the ability to monitor a permeation test constantly without the need to take periodic, discrete samples. IR systems are relatively stable and do not require a full-time attendant. Breakthrough time is very easy to discern. Perkins and Ridge acknowledge

that there are disadvantages, but the disadvantages may have workable solutions.

The third paper, written by *Spence*, addresses the difficult problem of directly comparing and characterizing the permeation resistance of different protective clothing materials. *Spence* cites this problem as particularly severe when attempting to compare generic materials containing varying amounts of raw materials and additives. This paper presents a solution: a standard set of permeation tests using nine chemicals selected on the basis of their solubility parameters. The rationale and usefulness of such a standardized test battery are discussed.

Recent technological advances have resulted in the use of absorptive fabrics in protecting against low levels of toxic vapors. In this final paper on test methodology, *Baars, Eagles, and Emond* describe a test apparatus and method designed for evaluating the performance of such absorptive fabrics. Carbon tetrachloride at a concentration of 5.0×10^{-6} g/cm³ was used as the standard challenge in an apparatus based on a design given in the military specification for cloth, laminated, nylon tricot knit, polyurethane foam laminate for chemical protection (MIL-C-43858). Permeated carbon tetrachloride was detected by using flame ionization.

Performance Data

Henry utilized ASTM Test F 739-81 to generate data on the permeation resistance of glove or ensemble materials exposed to chlorine gas, liquid hydrogen cyanide, and 37% formaldehyde solution. In his paper, *Henry* presents his performance results, but also ties the final selection process into an evaluation of the resistance of materials to physical hazards.

Forsberg, Olsson, and Carlmark then present a model testing program for meeting performance requirements of gloves to be used against metal cutting fluids in workshops and in steel handling processes. Chromium and nickel particulates can be carried through some glove materials by cutting fluids. The author combines permeation resistance with data on puncture resistance and tensile strength.

In his paper, *Mellström* carries the use of permeation testing a step further. He describes a data base combining permeation resistance data with medical and industrial hygiene information to provide an up-to-date source for assessing risk of chemical exposure. Currently in an experimental stage, the data base is available for use on a microcomputer through the Swedish National Board of Occupational Safety and Health.

A more detailed analysis of the permeation phenomenon is provided by *Schlatter and Miller* in their paper on material thickness versus permeation resistance. The authors, through testing five industrial chemicals against different thicknesses of five unsupported glove materials, conclude that a change in thickness is more likely to affect breakthrough time than the steady-state permeation rate.

In the last paper in this section, *Winter* describes a system developed for archiving permeation resistance data in a computer data base. This system is intended to provide the safety and health professional with rapid access to performance data in graphical form. Further, the professional would be able to compare directly different clothing materials against a single chemical or different chemicals against a single clothing material.

Resistance to Pesticides—Field Performance and Cleaning Procedures

Field Performance

Worker exposure to agricultural chemicals is just now emerging as an area of critical concern to safety and health practitioners. Although exposures have always existed, the geographical diversity and nature of farm workers themselves have contributed to a slow recognition of the extent and seriousness of the problem.

In the first two articles of this section on pesticides and protective clothing, the authors review the current state of the use and integrity of protective clothing. *Nielsen and Moraski* take a historical perspective to help identify monitoring and research needs pertaining to the agricultural worker. Priorities for a protective program, under the guidance of the U.S. Environmental Protection Agency, are discussed. *Rucker, McGee, and Chordas* then explore attitudes and practices of California pesticide applicators. The three coauthors identify growers as the group at highest risk because of their use of more hazardous substances, combined with a superficial understanding of the need to take precautions.

Branson, Ayers, and Henry prepared a paper describing their laboratory evaluation of seven protective clothing fabrics. The effectiveness of the fabrics was determined by exposing them to carbon-14 labeled solutions of commercially used pesticides. Their results indicate that some currently worn fabrics do not provide as much protection as commonly believed.

Lloyd follows this work in the United States with a description of a far-reaching study conducted in the United Kingdom. The author reviews a three-step process involving field and laboratory data gathering aimed at the development of national and international standards of performance for protective clothing used in pesticide spraying.

In another paper on the effectiveness of protective clothing, *Laughlin, Easley, and Hill* explore the impact of various fabric parameters and pesticide characteristics on permeation and penetration. The fabric parameters investigated were fiber content and functional finishes, while the pesticide characteristics were concentration and formulation. The work evolved as an effort to address a growing concern about accidental spilling of concentrated or diluted pesticides onto protective garments used by home gardeners, commercial applicators, and field workers.

Finally in this section, *Hobbs, Oakland, and Hurwitz* look at the effects of

barrier finishes on the pesticide penetration and comfort of woven and disposable nonwoven fabrics used by pesticide applicators. A laboratory test procedure was developed to evaluate the resistance of fabrics to oil-based and water-based pesticide carriers used as aerosol sprays.

Cleaning Procedures

Considerable research emphasis has been placed on decontamination of protective clothing after exposure to and contamination by pesticides. Both home and commercial laundering are currently in wide use, but with questionable effect.

Keaschall, Laughlin, and Gold evaluated the amount of residue remaining on or in three fabrics exposed to each of eleven pesticides. The fabrics were all identical cotton/polyester blends, but one was unfinished, the second was treated with a renewable consumer-applied fluorocarbon finish, and the third was treated with a commercially applied fluorocarbon finish. The fabrics were laundered using one of three treatments: a heavy-duty liquid detergent, a heavy-duty liquid detergent with a prewash spray, and a heavy-duty liquid detergent with an agriculturally marketed pretreatment. The resulting data show that residues after laundering vary considerably.

In a similar research program, *Leonas and DeJong* evaluated how functional finishes and different levels of laundering affect a fabric's ability to prevent or inhibit pesticide penetration. Three fabrics—cotton, cotton/polyester, and polyester—treated with selected functional finishes—durable-press, soil-release, and water-repellent finishes—were laundered 0, 10, 30, and 50 times. All the specimens were exposed to methyl parathion spray. Again, there was a wide range in measured performance.

Obendorf and Solbrig used electron microscopy to determine the relative distribution of malathion and methyl parathion on cotton/polyester unfinished and durable-press fabrics before and after laundering. In their paper, the authors conclude that laundering can remove up to 70% of each pesticide from the surfaces of the fibers, but has little effect on the pesticide accumulated within the lumen of cotton fibers. Results with the durable-press-finished fabric did not differ significantly from those for the unfinished fabric.

Risk Assessment of Chemical Exposure Hazards in Selecting Protective Clothing

Most chemical protective clothing demonstrates some level of permeation by toxic chemicals. A steady-state rate of release with the garment material acting as a toxic reservoir is possible after breakthrough of a chemical. The question therefore arises: What is an acceptable level of dermal exposure?

Many variables distinguish the level of risk to a worker. These include the toxicity of the chemical or chemicals, the absorption into the skin, and the

rate and location of contact. Confounding the evaluation of an acceptable level of skin exposure to toxic chemicals are the pragmatic issues of combining costs with overall benefits, including reuse.

This section of the STP deals with the need to assess risks and costs concurrently.

Mansdorf, in the lead paper in this section, suggests the need for a series of recommended dermal exposure levels and a field-validated method for quantitatively measuring exposures inside protective garments, including gloves. If developed, these suggestions would directly lead to a correlation between the steady-state permeation rate after breakthrough and acceptable dermal exposure levels.

As a means of measuring the absorption of organic solvents through the skin, *Boman and Wahlberg* describe an animal model intended to replace human experimentation. In their paper, the authors demonstrate that the animal model is also applicable to testing the protective effect of glove materials.

Schwöpe has prepared a paper that provides background information for those with little or no knowledge of chemical permeation through the skin. He presents an overview of the structure of the skin, methods for assessing skin permeation, and examples of published data.

Coletta and Spence then continue in the theme of risk assessment by describing five key elements important to the success of a chemical protective clothing management program. These elements form the basis for an ongoing risk/benefit analysis intended to ensure maximum employee protection within constraints imposed by operating and business considerations. The paper concludes with a case study.

A paper by *Forsberg* groups protective clothing materials into several different classes or categories on the basis of permeation data. Categories are proposed, based on three intervals of breakthrough time and five levels of steady-state permeation rate. The author also proposes applying a labeling and classification system to provide ready information for the risk assessment process.

In the last paper on risk assessment, *Berardinelli and Roder* develop the concept of quantitatively testing protective clothing in the field. The two authors present a scenario for evaluating clothing materials' resistance to degradation, permeation, and penetration by liquid chemicals.

Testing the Chemical Resistance of Seams, Closures, and Fully Encapsulated Suits

Laboratory evaluation of the chemical resistance of protective clothing materials provides base-level data on expected performance. However, the integrity of complete garments and their accessories before and after use is just as important as that of the base materials.

The first paper in this set, by *Berardinelli and Cottingham*, presents an

evaluation of penetration through bulky seams and closures using the ASTM Test for Resistance of Protective Clothing Materials to Penetration by Liquids (F 903-84). Eight different seams and closures were tested against several liquids. Specimens without seams or closures served as controls.

Garland, Goldstein, and Cary describe the use of a test booth for evaluating fully encapsulated chemical suits in a simulated work environment. Included in the test protocol are three exercises simulating typical work activities. A number of suit designs and concepts, including limited use of disposal clothing, have been tested. The results have led to modifications in design to improve performance.

Moore writes about his thesis that one set of use and maintenance guidelines may be developed to aid users of fully encapsulated suits. This may be true regardless of the fact that six or seven manufacturers currently draw upon three or four base materials for their individual designs and configurations. Moore notes that his data show that the differences mostly occur in closure systems, dump valves, glove-to-sleeve joints, and pressure-sealing zippers, rather than in the bodies of the suits themselves.

The "age-old" issue of protective clothing decontamination for reuse after chemical exposure is addressed by *Ashley* in this section's final paper. The author looks at two key issues. The first is a decontamination methodology to remove polychlorinated biphenyls (PCBs) from fire-fighters' protective clothing. The second is a technique for minimizing damage to protective clothing while subjected to the decontamination process. Removal efficiencies up to greater than 99% for PCBs have been achieved using a Freon solvent technique.

Laboratory Measurement of Thermal Protective Performance

A paper by *Hoschke, Holcombe, and Plante* reviews the merits and deficiencies of some existing and proposed test methods for evaluating fabrics intended for protection against radiant heat and flame. Standard test methods for thermal protection of clothing and materials, including British Standard 3791, International Organization for Standardization (ISO) Standard 6942, and the ASTM Test for Thermal Protective Performance of Materials for Clothing by Open-Flame Method (D 4108-82) are considered, as well as the radiant heat test method proposed in Federal Aviation Administration Report FAA-RD-75-176. These test methods are discussed on the bases of the heat source, the design of the heat sensor, and the method of specimen mounting. The authors suggest modifications to improve the testing apparatus and procedures.

In another paper, *Holcombe and Hoschke* describe the role of the protective garment during intense heat exposure and discuss how current laboratory test methods relate to typical heat hazards. They express the concern that current standards pay too little attention to the nature of the working environ-

ment. According to the authors, consideration should be given to development of a test to simulate intense radiant heat exposure, which, they argue, better simulates flame exposure incidents than convective heat tests. They believe that in setting performance requirements for protective clothing, it is essential that the relative risks be properly balanced and that undue emphasis not be placed on aspects that are not warranted according to injury statistics. They propose that more attention be devoted to the need for materials that reduce the risk of metabolic heat stress in hot working environments.

Schoppee, Welsford, and Abbott discuss factors affecting the thermal performance of protective clothing. The authors believe that the effect of heat exposure on the strength of fabrics is an important consideration in their protective ability. They show that strength retention during short-term exposure to high-intensity radiant and convective heat depends on the temperature reached at a given instant during exposure. It is independent of the mechanism of heat absorption. Their experiments predict that high-temperature materials such as polybenzimidazole (PBI) and Nomex/Kevlar can provide a few extra seconds of protection to the extreme heat of a large fire. This paper covers problems associated with the use of an instrumental skin-simulant device to determine the rate of conductive heat transfer through fabrics of various kinds. It concludes that ranking fabrics by the maximum temperature achieved in the skin simulant is the only reliable way of using data from this device.

Shalev and Barker describe the use of novel experimental techniques to explain the characteristic responses of PBI, aramid, and flame-resistant cotton fabrics in laboratory tests of thermal protective performance. They show that thermophysical properties change extensively during exposure to intense heat ($2.0 \text{ cal/cm}^2/\text{s}$) in a thermal protective performance (TPP) test. The polymer-to-air ratio emerges as an important variable predicting TPP in flame exposures. The mechanism by which thermal insulation is maintained depends on the fiber or flame-retardant (FR) finish. The authors speculate that the ablative effect of moisture loss, along with retention of the air volume fraction, contributes to improving the thermal protective performance of PBI fabrics in a convective exposure. According to this study, the ability of a fabric to maintain surface fibers impacts significantly in flame heat transfer. The findings presented here demonstrate why vapor-phase active flame retardants, which suppress air gap ignition when treated cotton fabrics are tested, perform better in a TPP exposure than cotton fabrics treated with solid-phase flame retardants.

Schleimann-Jensen and Forsberg describe a new test method for evaluating protective materials in exposures to infrared (IR) radiation. Their test equipment uses an IR thermometer which, without contacting the test specimen, computes the surface temperature by measuring radiation transmitted through the fabric. The authors report that this method is useful as a means of characterizing the emissivity and reflectivity properties of protective mate-

rials in radiant heat exposure. They suggest that the method is suited for use as a screening test for materials intended for high-intensity radiation exposures.

Evaluating Materials for Thermal Protective Clothing

Bouchillon summarizes the physical, thermal, and fire protection characteristics of fabrics prepared from Celanese PBI fibers blended with other fibers (for example, FR rayon, aramids). Data are presented on the properties of PBI including flame resistance, thermal stability, chemical resistance, and comfort. Bouchillon describes applications for PBI in industrial protective apparel. He discusses the properties of PBI-containing fabrics measured in laboratory tests intended for predicting performance in high-temperature gloves, foundry and fire proximity equipment, and fire-fighters' protective clothing.

Benisek, Edmondson, Mehta, and Phillips discuss the performance of FR wool and other heat-resistant fabrics in tests against flame and exposure to molten metal. The types of fibers and flame-retardant compounds are shown to play an important role in the transfer of dangerous heat through clothing fabrics. The authors find that fabric construction parameters are important in protection against flames and molten metal. They conclude that moisture plays a large role in thermal protective performance. In multilayer clothing assemblies moisture in outer fabrics increases protection against flame, while the accumulation of moisture (body perspiration) in the inner layer decreases protection against flame. The authors discuss the results of interlaboratory evaluations of two draft ISO test methods for molten metal splash.

The paper by *Baitinger and Konopasek* investigates the thermal protective performance of FR-treated cotton fabrics. The thermal insulative performance of single-layer and multiple-layer fabric assemblies is compared in purely radiant and convective heat exposures ranging from 0.30 to 2.0 cal/cm²/s in intensity. The authors find that, at 1.0 and 2.0 cal/cm²/s heat flux levels, fabric weight and thickness are directly related to thermal protection. Air spacing in multiple-layer clothing systems is found to be a significant contributor to insulation.

Mischutin and Brown describe cotton fabrics treated with Caliban flame-retardant finish. The Caliban finish is described as an aqueous dispersion of decabromodiphenyloxyde and antimony trioxide. They discuss a new hydrophylic butyl acrylic binder system designed to improve the water vapor and air permeability of Caliban-treated cotton fabrics, without loss of softness or durability. They present data on the physical properties, flame resistance, and performance of Caliban-treated cotton fabrics in a molten aluminum pour test.

Dixit reviews the development of high-temperature gloves made with Zetex, a trademark name for a highly texturized fiberglass fabric. He compares

Zetex fabrics and asbestos fabrics in a laboratory test intended to measure the insulation that gloves provide in handling hot metal pipes. Dixit reports that Zetex gloves, although lighter in weight, provide better insulation than gloves made with asbestos. He compares the abrasion resistance of texturized glass fabric and asbestos fabrics, including performance in a splash test against molten iron.

Clothing Systems for Industrial and Fire-Fighting Applications

Krasny reviews principles of clothing protection in fire situations and gives examples of test results on materials used in heat protective garments. He discusses turnout coats for structural fire fighters and work garments to be worn in areas where accidental fire may occur. He gives examples of measurements of heat protective properties. The materials covered are single layers of fabrics appropriate for work uniforms, the same type of fabric combined with four popular underwear fabrics, and typical fire-fighters' turnout coat assemblies, consisting of a shell fabric, vapor barrier, and thermal barrier.

Jaynes describes a method developed at the Inland Steel Co. to evaluate the resistance of protective clothing materials to molten metal splash. He discusses factors affecting molten metal splash testing and compares the performance of various heat-resistant fabrics in these tests. Jaynes describes, from the viewpoint of a safety engineer, the relationship between laboratory measurements of molten metal splash resistance and protection in an industrial environment.

Veghte discusses factors to be considered in the design of fire-fighters' protective clothing. He reviews the development of heat resistant materials and standards for thermally protective clothing. Veghte reports on a recent tabulation of fire-fighters' injuries and shows the relationship between specific body regions and burn injury. He summarizes data on the temperatures and heat flux levels associated with conditions encountered in fighting structural fires. He presents the results of TPP tests made on a number of fabric ensembles used in fire-fighters' protective equipment. These data are presented to illustrate the merits of matching the thermal responses of the vapor barrier and thermal liner under the outer protective shell. Veghte cites examples illustrating the effect that moisture in the thermal liner component has on the protective insulation of fabric ensembles.

Audet and Spindola describe the U.S. Navy's effort to develop fire-retardant/heat-protective clothing for shipboard personnel. They discuss the use of laboratory material tests including vertical flammability tests and protection time determinations for both flame impingement and radiant heat exposures. They describe field testing involving exposure of garments on instrumental manikins to estimate the extent of burn injury sustained or protection times provided by various clothing ensembles. They find that the usefulness of laboratory tests for predicting clothing performance in actual fire situations is

somewhat limited because of the variability of the exposure encountered in a large-scale fuel fire. However, they conclude that laboratory tests are extremely useful as screening tools to limit the number of candidate systems that need to be evaluated under field conditions.

Heat Stress, Fit Testing, and Other Performance Requirements for Protective Clothing

A paper by *Gonzalez, Breckenridge, Levell, Kolka, and Pandolf* addresses the need to reduce the danger of heat exhaustion for persons who must wear impermeable chemical protective garments in hot environments. They suggest that a feasible approach is the use of a wettable cover over the impermeable garment. The theory is that an increase in skin heat loss can occur from such a wet cover over a garment. The authors describe a biophysical approach which allows prediction of the cooling benefits from a wetted cover over an impermeable ensemble.

Davies describes the development and evaluation of a specialized clothing system designed to provide a thermally comfortable environment for workers during access to an advanced gas-cooled nuclear reactor system. The system uses a vortex cooling effect to maintain a comfortable environment inside a pressure suit. The author concludes that this approach provides adequate protection for persons working for extended periods in abnormal environments.

A systematic method for garment fit testing and evaluation is covered in a paper by *McConville*. *McConville* believes that a major challenge facing designers and manufacturers of protective clothing and equipment is the establishment of a sizing system to accommodate the body size variation of the user population as well as to provide a good fit for individuals. He advocates replacing trial-and-error methods with careful application of anthropometric design data. He provides guidelines for conducting such a fit test. Examples cited in this paper concern protective clothing for military uses. However, the author suggests that the principles could be applied for the sizing of protective apparel for other wearer populations.

Robinette also reports problems with current garment sizing practices and presents a method for sizing intended to improve the situation. Her paper demonstrates how an anthropometric system can result in garments that fit people better. She discusses several benefits to be gained by using a systematic sizing approach for protective clothing. *Robinette* cites advantages gained in workers' safety and productivity. She lists the benefits associated with realistically proportioned clothing and better information concerning the demand for particular garment sizes.

Gordon demonstrates the application of an anthropometric approach to garment sizing and fit testing. Her paper reports on the development of integrated sizing systems for the U.S. Army's battledress uniforms. She discusses

the problems associated with the introduction of two separate field uniform systems for men and women. She shows how anthropometric sizing methods are applied to derive a single sizing system for both men's and women's uniforms.

The danger of fire or explosions caused by electrostatic spark discharge from the human body or from clothing is discussed in a paper by *Wilson*. The purpose of this research was to determine the critical voltages required for the ignition of flammable gases by spark discharges from the body. The author describes experiments with spark discharge from the body to metal electrodes of various diameters and temperatures. He concludes that the temperature of the metal surface to which the spark is passed is the main factor controlling the body voltage required to ignite mixtures of methane and air.

Concluding Remarks

The research discussed in this volume contributes to the body of authoritative literature on protective clothing. The editors hope that these findings will focus additional efforts in this important area, an area that has impact on the safety and health of hundreds of thousands of workers throughout the world.

Roger L. Barker

North Carolina State University School of Textiles, Raleigh, NC 27650; symposium chairman and editor.

Gerard C. Coletta

Risk Control Services, Inc., Tiburon, CA 94920; symposium chairman and editor.