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Project Summary

Fluorescent Tracer Evaluation of Protective Clothing Performance

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Field studies evaluating chemical protective clothing (CPC), which is often employed as a primary control option to reduce occupational exposures during pesticide applications, are limited. This study, supported by the U.S. Environmental Protection Agency (EPA), was designed to evaluate several protective garments and to determine the ability of specific CPC components to reduce worker exposure. The studies, conducted in central Florida during citrus applications of Ethion 4 Miscible™, examined cotton workshirts and workpants, cotton/polyester (C/P) coveralls, SMS coveralls, and Sontara coveralls. CPC performance was evaluated by fluorescent tracers and video imaging analysis and by the patch technique. Nonwoven coveralls allowed significantly greater exposure than did traditionally woven garments primarily because of design factors (e.g., large sleeve openings). Fabric penetration occurred with high frequency for all test garments, and none can be considered chemically resistant under these field conditions. Improved coverall garments would, however, provide only a small further reduction in exposure. Faceshields would reduce the exposure approximately three times more than would improved coveralls. Exposure pathways that would probably be undetected or inaccurately quantified by the patch technique were measured by fluorescent tracers and imaging analysis. The patch technique, however, was far more sensitive in detecting fabric penetration. Workers conducting airblast applications would be better protected by closed cab systems or any other technology that places a well-defined barrier between the worker and the pesticide spray. Personal protective equipment (PPE) requirements should consider the potential for heat stress, and conditions under which PPE is not to be used should be defined and enforced to reduce the risk of illness related to heat stress. Protective garments designed and marketed for use by pesticide applicators should be field tested to determine performance, and users should be provided with accurate information regarding the chemical resistance of such garments.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

CPC is often employed as a primary control option to reduce occupational exposure during pesticide applications. CPC has traditionally been evaluated in two phases: laboratory and field performance testing. Although laboratory testing can provide information about pesticide penetration through fabric, field testing under realistic exposure conditions is needed to determine the overall efficiency of reduced penetration. Design factors that enhance or reduce exposure are evident only during field use of the clothing.

Field methods to evaluate CPC performance are limited. The patch technique, which places collection pads above and beneath clothing to estimate garment penetration, can produce highly variable measurements since pesticide exposure during applications is, in most cases, not uniform. Exposure may also occur by pathways that the patch technique was not intended to detect; e.g., deposits through openings in garments or by cross-contamination. The use of fluorescent tracers and video imaging analysis provides an opportunity to conduct realistic field performance evaluation of CPC. This technique allows visualization of exposure patterns on the skin and quantitative estimates of pesticide deposition.

The primary objective of this study was to evaluate the performance of CPC under realistic pesticide application conditions. Specific aims were to (1) identify dermal exposure pathways, (2) compare dermal exposures of workers wearing test garments to those of workers wearing traditional protective clothing, (3) determine the scientific validity and feasibility of employing the fluorescent tracer technique as an evaluation method, and (4) determine the ability of specific CPC components to reduce total worker exposure. The overall study was divided into two components: the Protective Clothing Performance Study, designed to address aims one through three, and the Total Exposure Distribution Study, designed to address the fourth aim.

Methods

Field studies occurred in central Florida during citrus applications of Ethion 4 Miscible™ [EPA Reg. No. 279-1254]. Ethion 4 Miscible™ is a liquid concentrate formulation containing 4 lb active ingredient (AI)/gal and is 46.5% AI by weight. The active ingredient is the organophosphorus insecticide, ethion [0,0,0',0'-tetraethyl S,S'-methylene bisphosphorodithioate]. All applicators were adult males who applied pesticides as part of their normal work duties.

Four garment types were selected for evaluation in the Protective Clothing Performance Study: two were traditional garments used in agriculture and two were made from nonwoven fabrics selected by EPA investigators. Fabric characteristics were as follows:

- *Cotton workshirt + workpants* (woven, untreated): 100% cotton twill material; twill woven construction;
- *C/P coverall* (woven, untreated): a 65% cotton/35% polyester twill material; twill woven construction;
- *SMS coverall* (nonwoven, treated): 100% polypropylene composite material with three-layered construction; thermally pointbonded laminate of spunbonded, melt blown, spunbonded fabric;
- *Sontara coverall* (nonwoven, treated): 50% polyester, 50% wood pulp material with both pointbonded and spunbonded construction; spunlaced composite.

Eight replicate exposures of each garment were proposed based on previous studies that indicated statistical differences in garment performance with a similar sample size. Each applicator in the study wore each of the garments at least once to minimize potential confounding resulting from personal application procedures. Equipment type, tank size, and amount of fluorescent tracer applied per tank were controlled for all applications in Year 01. Uncontrolled variables included number of tanks applied, application time, and individual work practices. Each applicator was given a black, cotton T-shirt, chemical-resistant gloves, and one of the protective garments to wear. Mixers were not monitored during this study.

Participants in the Total Exposure Distribution Study conducted replicate applications of ethion under normal field conditions. Two protective coveralls (cotton and Sontara) were assigned to applicators on a random basis. In one-half of the replicate applications, protective gloves also assigned on a random basis were worn. All applicators wore plastic face shields. Fabric characteristics were as follows:

- *Cotton coverall* (woven): a 100% cotton denim material; twill woven construction; untreated;
- *Sontara coverall* (nonwoven, treated); described above.

Twelve replicate tests of each garment were conducted, with each participant wearing each type of garment four times.

The Ethion 4 Miscible™ formulation was applied throughout the study according to label instructions. Natural oil and other agricultural chemicals (e.g., copper, Benlate™, Kocide)™ were frequently added to the spray mixture. In some cases, no ethion was included in the spray mix. All applicators used airblast sprayers with 500-gal tanks pulled by open-air tractors with a top canopy for shade. Each worker was monitored during application of four 500-gal tanks. A commercially available fluorescent whitening agent, Calcofluor RWP (4-methyl-7-diethylaminocoumarin), was employed as a tracer of pesticide residue deposition. Tracer concentration in the spray mix was constant throughout the studies (300 gm per 500 gal H_2O; 160 ppm).

Protective Clothing Performance Study Sampling

Pre- and post-exposure video images were made of each subject's hands, head, neck, forearms, upperarms, upper torso, and lower torso. All images were acquired using a second generation video imaging analysis system. Fluorescent tracer deposition patterns were also evaluated qualitatively by visual observations and scoring. Dermal patches were attached above and below the protective garment on the thighs to estimate protective clothing penetration. Images were analyzed with the customized C-language software programs, VITAE-MAP and VITAE-CALC. Post-exposure images were outlined to isolate the body region of interest and then were superimposed onto the pre-exposure images. Histograms (grey level frequency distributions) of these images were then subtracted, and the net fluorescence was transformed to tracer mass by means of a standard curve. The data for the standard curve was developed in the laboratory by spotting known amounts of the tracer on human skin. Patches were cold-solvent extracted and analyzed for ethion by electron capture gas chromatography. The same extracts were analyzed for the tracer by spectrofluorometry.

Total Exposure Distribution Study Sampling

The traditional patch technique recommended for applicator exposure assessment was employed with minor modifications. Twenty alpha cellulose patches were positioned on each worker. A pair of patches (one on the outer garment and one inner patch on the skin) were attached to the upper legs (4), lower legs (4), upper arms (4), and lower arms (4), chest (2), and back (2). After a worker was suited in a protective garment, both hands were washed with ethanol by placing the hand in a plastic bag containing 250 ml ethanol; wrapping the mouth of the bag tightly around the wrist; relaxing the hand; and having a staff member shake the hand in the solution for 30 sec. This procedure was repeated twice for each hand. After the worker finished spraying his tanks, this handwash procedure was repeated. All workers' hands were washed regardless of whether they worked bare-handed or wore gloves. All workers' wore faceshields that extended from forehead to chin. When the worker returned from spraying, field staff removed his faceshield and wiped the entire face of the shield with an ethanol-moistened gauze pad.

Results

Protective Clothing Performance

Thirty-three applications of insecticide involving six workers were monitored; the Sontara garment was worn in nine applications and each of the other three garments were worn in eight applications. Tracer concentration was maintained at 300 g/tank for all applications, but ethion concentration varied substantially. The total amount of tracer and ethion AI applied ranged from 0.4 to 1.2 and 0 to 10.9 kg, respectively. Fluorescent tracer exposure measurements produced by video imaging analysis were normalized to reflect a standard application of four tanks and expressed as an hourly rate. In all cases, tracer exposure beneath protective clothing was greatest for the forearms. Mean forearm exposure was lowest for the workshirt (34 µg/hr), and exposure was lower for the C/P coverall than for either of the nonwoven coveralls 64 µg/hr for C/P coveralls compared with 87 and 93 µg/hr for SMS and Sontara garments, respectively). A similar exposure pattern observed for the upper arms was not evident for the torso. Variability within each garment group was high for all body regions, with coefficients of variation ranging from 89% to 260%. Neither parametric (ANOVA) nor nonparametric (Kruskal-Wallis) tests among garment types yielded significant differences.

A substantial amount of the variability observed across garment types was believed to be due to differences in garment challenge; i.e., the amount of fluorescent tracer reaching the outside of the garments and the exposed skin surfaces. Head exposure provides an indication of the tracer challenge that each worker received during application, since none of the workers wore PPE for this region. Exposure data for the forearms, upper arms and torso were therefore normalized by the average head exposure (96.7 µg/hr) for the entire study group as follows: a challenge adjustment factor was calculated by dividing the group mean head exposure by each individual's head exposure; each individual's forearm, upper arm and torso exposure values were then multiplied by this adjustment factor to produce normalized exposure data for these body regions. If differences in individual challenge are contributing to the variability observed within garment groups, then this adjustment should reduce within-group variability and allow a more direct assessment of the effect of garment type on exposure to protected regions. The adjustment decreased the coefficient of variation (CV) in 10 of 12 cases, with the range of CVs reduced from 89% to 260% to 64% to 192% (Table 1).

The pattern of exposure between woven and nonwoven garments remained similar to that observed in the original data set, but the pattern within nonwoven garments was altered such that the SMS garment exhibited higher adjusted exposure than did the Sontara garment for all body regions. Statistical analysis of the challenge-adjusted data by the Kruskal-Wallis test indicated the following: forearm exposure was significantly higher for the SMS garment than for the other three garments; forearm exposure was also significantly higher for the Sontara garment than for the woven garments; upper arm exposure was significantly higher for the Sontara garment than for the two woven garments; upper arm exposure was probably higher for the SMS garment than for the workshirt and woven coveralls, but differences were not statistically significant at this sample size; no significant differences in torso exposure were observed. The detection of high levels of tracer on the forearms for the nonwoven garments suggests that dermal exposure occurred by spray entering through the sleeve opening. The detection of relatively high levels of tracer on the upper arms for the Sontara garment suggests that both fabric penetration and deposition through the sleeve opening contributed to exposure.

Scores based on visual observations following application corresponded well to the imaging analysis results (Figure 1). Torso exposure was not significantly different across the garment types (ANOVA: $p<.05$), but both upper arm and forearm exposures were different. Visual scoring indicated even more pronounced differences between the woven and nonwoven garments for the arms and for the forearms in particular. It was also apparent during visual observation that arm exposure decreased with increasing distance from the wrist and that most torso exposure occurred at or near the neck. These observations suggest that in the majority of cases the tracer was being deposited on skin by movement *under* the garment rather than through fabric (Figure 2).

Ethion exposure (Table 2) was estimated by multiplying the fluorescent tracer exposure data by the average ratio of ethion and tracer deposited on outer patch samplers on the upper region of the body (chest, shoulder, and head). Since workers applied widely varying amounts of ethion, average ethion/tracer ratios were calculated for applications with 5 pints Ethion 4 Miscible™ per 500-gal tank and 12 pt/500 gal tank. These ratios averaged 8.90 ± 4.4 and 21.34 ± -8.4 for the 5 pt and 12 pt/tank concentrations, respectively. Despite a broad range of ratio values within each group (4 to 19 and 9 to 35, respectively), the proportion of the average ratios was virtually identical to the 2.4 proportion of pt/tank (12pt/5pt).

Percent penetration of ethion through protective clothing was calculated dividing the inner patch sampler value by the outer patch sampler value and multiplying by 100. In Year 01, garment breakthrough occurred in all of the 23 applications for which complete data were available. Mean penetration values for the four garments were quite similar, ranging from 4.7% - 7.2%, and did not differ significantly. In Year 02, ethion penetration at the legs was greater for the cotton coveralls than for the Sontara coveralls (2.7 versus 0.8; KW: $p<.02$). The same pattern was observed for the chest, but this was not statistically significant because of the high variability within each garment type (5.4 versus 1.4; KW: $p=.17$). Ethion penetration of the Sontara garment was much lower in Year 02 than in Year 01 (0.8% versus 6.3% penetration at the legs). Comparing the woven coverall garments across the years indicated that the 100% cotton coveralls performed more effectively than did the C/P coveralls (2.7% versus 4.7% penetration at the legs).

Total Exposure Distribution Study

Twenty-four applications were monitored: 12 in which the cotton coverall was worn and 12 in which the Sontara coverall was worn. All exposure data are expressed as hourly rates (µg/hr) based on a measured application rate of 17 min/tank. Hand exposure without gloves averaged 13,812 µg/hr, and ranged from 2000 to 23,000 µg/hr. When nitrile gloves were worn, exposure decreased nearly eightfold to 1,762 µg/hr, with a range of 193 to 9,370 µg/hr (ANOVA: $p<.0001$). Clearly, use of gloves substantially reduced, but did not eliminate, hand exposure. Face and head exposures were calculated by extrapolating the average of four torso patch samplers to the relevant surface areas (650 cm^2 for face, 1180 cm^2 for head). This calculation yielded an average face exposure value of 965 µg/hr and an average head exposure value of 1,752 µg/hr.

Table 1. *Challenge-Adjusted Fluorescent Tracer Exposure by Garment Type* (μg/hr)*

Garment Type	Forearms		Upper Arms		Torso	
	Mean	CV (%)	Mean	CV (%)	Mean	CV(%)
Workshirt	46.2 $^{A+}$	64	1.7 $^{D+}$	149	30.9	97
C/P coveralls	56.3 $^{A+}$	108	4.1 $^{D+}$	192	24.5	70
SMS	388.9 $^{B+}$	89	107.8	138	82.0	154
Sontara	109.8 $^{C+}$	71	19.8 $^{E+}$	82	39.9	131

** These values have been normalized by group mean head exposure.*
$^{+A\text{-}E}$ Values within columns with different letters are significantly different (Kruskal-Wallis; $p<.05$).

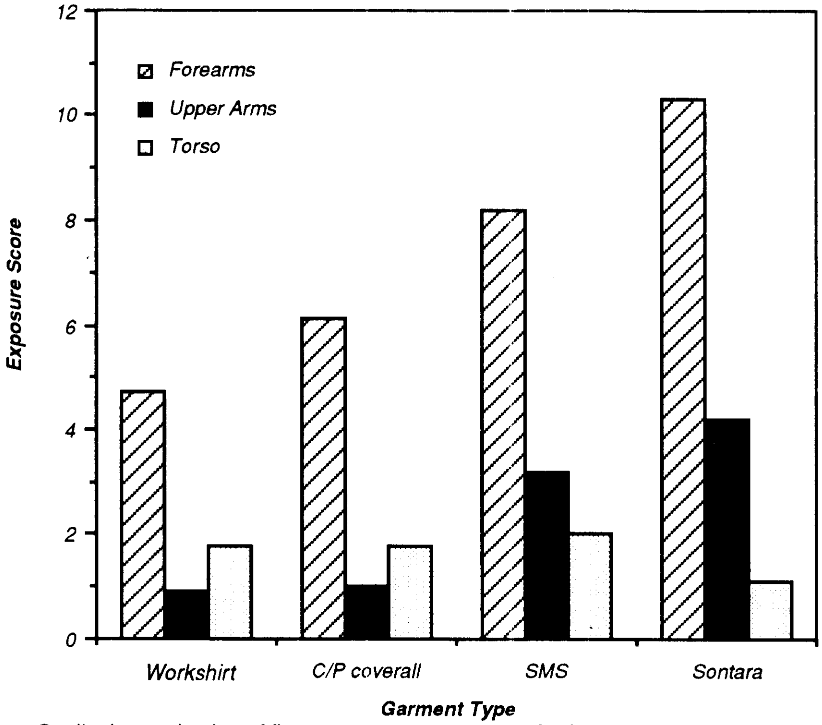

Figure 1. *Qualitative evaluation of fluorescent tracer exposure for four test garments by body region.*

Inner patch samplers were categorized as either (1) quantifiable (>0.84 μg/sample), (2) trace (0.24-0.84 μg/sample), or (3) unexposed (<0.24 μg/sample). In the majority of cases, garment breakthrough occurred for the body regions protected by coveralls (Table 3). For cotton coveralls, 34% of the inner patch samplers had quantifiable ethion and an additional 29% had trace levels, resulting in a breakthrough frequency of 63%. For the Sontara coveralls, 26% of the inner patch samplers had quantifiable ethion and an additional 43% had trace levels, resulting in a breakthrough frequency of 69%. Exposure to regions beneath protective garments was calculated by multiplying the inner patch sampler deposition rate by the appropriate standard surface area. Only quantifiable ethion and trace values were used, with trace values being assigned one-half the limit of detection (007 μg/cm^2); unexposed samples were assigned values of zero. Total exposure to these regions was then determined for each worker, and average "protected body" exposure was determined (protected body is defined here as all regions beneath coveralls).

The distributional characteristics of exposure are important in that they indicate the effectiveness of specific interventions for reducing exposure and provide data for recommending additional interventions. Numerous applicator exposure studies have reported the distribution of dermal exposure across body regions, but most often these studies have lacked specificity concerning methods of calculations, use of PPE, and underlying assumptions. Furthermore, traditional sampling techniques may have underestimated exposure beneath protective clothing because of deposition through garment openings, as documented here. As a result, generalizations sometimes cited concerning exposure distribution may be inaccurate. Based on the data collected in this study, a series of exposure scenarios has been developed to identify the role of PPE in exposure reduction. These data are believed to be representative of airblast applicator exposure in citrus orchards, and they may be representative of orchard airblast exposure in general. They are not, however, applicable to other types of pesticide applications (e.g., groundboom, backpack), nor do they reflect exposure patterns of pesticide mixers or mixer/applicators.

Label requirements for Ethion 4 Miscible™ require that a worker wear the following PPE during application: (1) protective suit of one or two pieces covering all parts of the body except the head, hands and feet; (2) chemical resistant gloves and shoes; (3) National Institute for Occupational Safety and Health or Manufacture's Safety Association approved respirator. In practice, these requirements are not followed consistently during summer spraying of citrus in Central Florida. Indeed, there is substantial evidence to suggest that such requirements place an undue burden on workers and may contribute to physiological conditions related to heat stress. It is not uncommon for workers applying under high temperature and high humidity conditions to forego the use of a respirator and to alter protective suits in a manner that allows greater air circulation to the body.

The realities of actual field use of PPE prompted the following scenarios to assess the role of specific PPE combinations in reducing dermal exposure. Exposure estimates generated by these scenarios are given in (Table 4). Since this study did not measure exposure to the feet, the use of chemical resistant shoes or boots is not discussed; exposure to this body region is assumed to be zero in subsequent calculations. Unfortunately, one PPE option—chemical resistant hoods—was not investigated in this study. Hoods would appear to provide substantial protection for all portions of the head except the face; however, no published studies are available to demonstrate the effect of hoods on head exposure.

SCENARIO 1: *The unprotected worker.* This scenario assumes that workers use virtually no PPE or that PPE is used in a manner that provides little protection. Thus, the hands, face and protected body regions (regions beneath coveralls) are considered unprotected. Deposition rates measured on the *outside* of coveralls have been used to estimate exposure to the protected body regions.

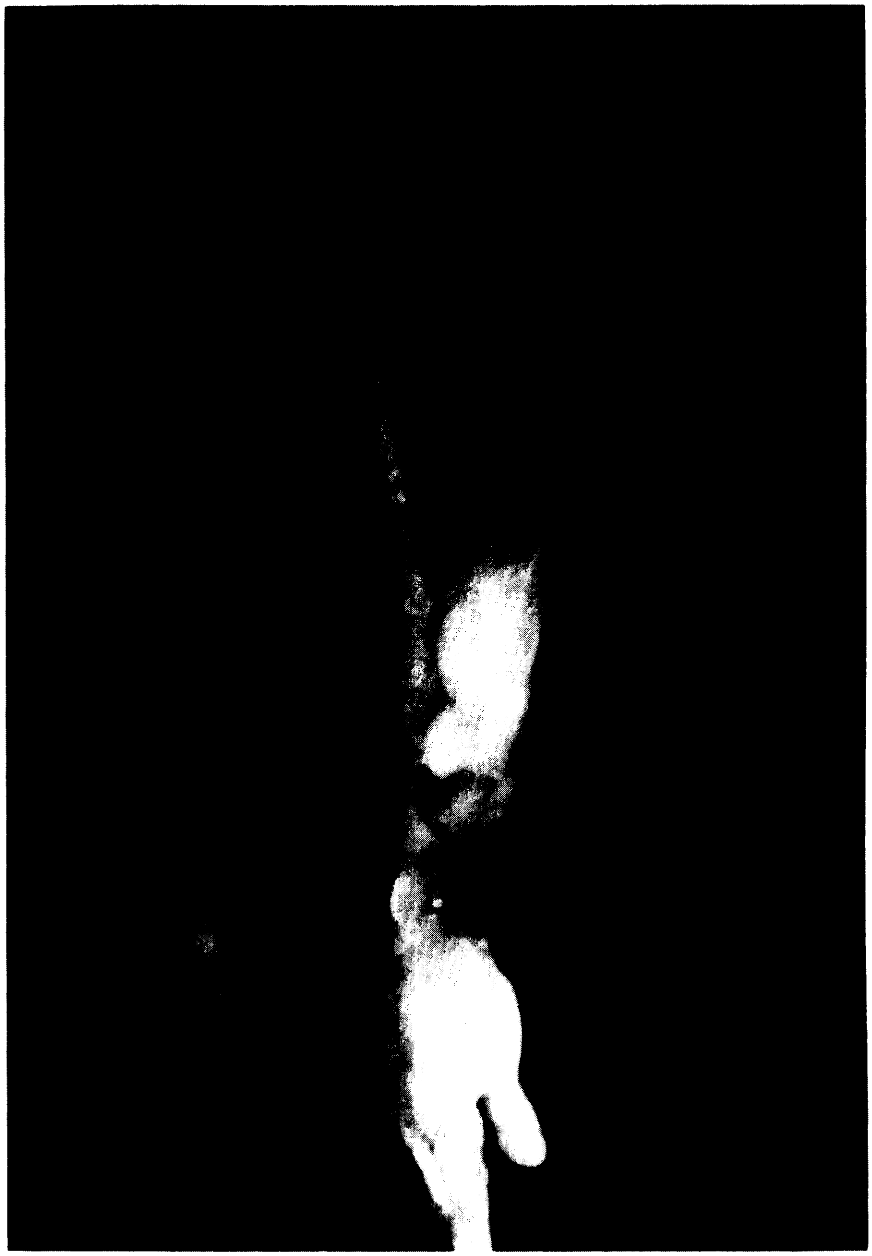

Figure 2. *Fluorescent tracer exposure beneath the sleeves of the nonwoven garments was common on the forearms and extended above the elbow in many cases.*

SCENARIO 2: *Cotton or Sontara Coveralls only.* Use of a protective coverall is added to Scenario 1. Hand and head estimates remain unchanged. This scenario assesses the effect of the coveralls used in this study but assumes that the worker does not follow label requirements regarding gloves.

SCENARIO 3: *Cotton or Sontara Coveralls + Gloves.* Use of chemical resistant gloves has been added to Scenario 2. Head and protected body estimates remain unchanged. This scenario assesses the effect of chemical resistant gloves on hand exposure and is consistent with label requirements.

SCENARIO 4: *Cotton or Sontara Coveralls + Gloves + Faceshield.* Use of a faceshield has been added to Scenario 3. Hand and protected body estimates remain unchanged. This scenario assesses the effect of the faceshield when a worker is following label requirements.

SCENARIO 5: *Chemical Resistant Coveralls + Gloves.* Chemical resistant coveralls (100% effective) have been substituted for the cotton or Sontara coveralls used in the study, and the faceshield has been removed. Head exposure is that used in Scenarios 1 through 3. Hand exposure remains unchanged from Scenario 4. This scenario assesses the effect of a truly chemical resistant coverall on total exposure when a worker is wearing label-required protective clothing. (It should be noted that no field studies to date have documented that commercially available coveralls perform in this manner during airblast applications.)

SCENARIO 6: *Chemical Resistant Coveralls + Gloves + Faceshield.* Faceshields have been added to the PPE in Scenario 5 to create a scenario in which all PPE options are combined.

Dermal exposure to the unprotected worker (S-1) was primarily to the protected body regions (73%), with hand exposure contributing nearly 24% of total exposure. The use of cotton or Sontara coveralls (S-2) reduced total dermal exposure by 73%, and exposure to unprotected hands became the primary contributor to total dermal exposure (87%). Thus, coveralls play the most important role of any PPE in reducing exposure during citrus airblast applications. Adding chemical resistant gloves (S-3) further reduced dermal exposure to 94% of that received by the unprotected worker when exposure is compared with workers wearing coveralls. The use of gloves reduced total dermal exposure by 76%. Under this scenario the contributions of protected hands and unprotected head were equal, accounting for more than 90% of total dermal exposure. The addition of faceshields (S-4) produced further, but slight, decreases in exposure (to 95% compared with the unprotected worker; to 81% compared with workers with coveralls), and hands again became the predominant source of exposure. When compared with Scenario 3, however, in which workers followed label requirements, exposure was reduced by 21%.

In light of the partial failure of the coveralls evaluated in this study to prevent exposure, it seems reasonable to ask whether improved coveralls would provide substantially greater protection. If 100% effective coveralls had been worn with gloves (S-5), only a slight decrease in exposure (to 94% compared to the unprotected worker; to 78% compared to workers with coveralls; only 6% compared to coveralls + gloves) would have occurred, with remaining dermal exposure distributed equally between the protected hands and unprotected head. Thus, use of

Table 2. *Ethion Exposure Estimates from Imaging Analysis for Protected Body Regions (μg/hr)**

Body Region	No. of Tests	5 Pints Insecticide Mean	5 Pints Insecticide Range	12 Pints Insecticide Mean	12 Pints Insecticide Range
Forearm					
Workshirt	8	300.8	18 - 650	721.3	43 - 1558
C/P Coveralls	8	573.2	18 - 1513	1374.3	43 - 3628
SMS	8	771.6	36 - 1905	1850.2	86 - 4567
Sontara	9	825.9	80 - 3222	1980.4	192 - 7725
Upper Arm					
Workshirt	8	12.5	1 - 62	29.9	0 - 149
C/P Coveralls	8	109.5	1 - 819	262.5	0 - 1963
SMS	8	159.3	1 - 890	382.0	0 - 2134
Sontara	9	191.4	9 - 854	458.8	21 - 2049
Torso					
Workshirt	8	175.3	0 - 730	420.4	0 - 1750
C/P Coveralls	8	331.1	18 - 1495	793.8	0 - 1963
SMS	8	195.8	9 - 1130	469.5	21 - 27104
Sontara	9	262.6	0 - 1237	629.5	0 - 29669

* Original fluorescent tracer exposure data have been multiplied by the mean ethion/tracer ratio for each ethion 4 Miscible™ application rate (8.90 for 5 pt/500 gal: 21.34 for 12 pt/500 gal).

Table 3. *Chemical Protective Clothing Breakthrough Frequency by Garment*

Garment	Total Patches	Quantifiable* Ethion	Percent	Trace† Ethion	Percent	Q + T ‡ Ethion	Percent
Cotton coverall	114	39	34.2	33	28.9	72	63.2
Sontara § coverall	96	25	26.0	41	42.7	66	68.8

*Quantifiable = > 28 pg/μl; > 0.84 μg/sample.
† Trace = < 28 pg/μl and >8 pg/μl; 0.24 - 0.84 μg/sample.
‡ Frequency of quantifiable + trace breakthrough.
§ One subject excluded due to very high deposition rates.

Table 4. *Dermal Exposure Reduction by Personal Protective Equipment (PPE)*

PPE Scenario	Percent Scenario 1	Exposure versus Scenario 2	Reduction Scenario 3	Total Dermal Exposure (μg/hr)	Percent Total Exposure: Hands	Head	Body
1 Unprotected Worker*	0	—	—	57,974	23.8	3.0	73.2
2 Cotton or Sontara† coveralls only	72.7	0	—	15,806	87.4	11.1	1.5
3 Cotton or Sontara coveralls + Gloves	93.5	76.2	0	3,756	46.9	46.6	6.4
4 Cotton or Sontara coveralls + Gloves + Faceshield §	94.9	81.2	20.8	2,974	59.2	32.6	8.2
5 Chem-Resistant coveralls # + Gloves	93.9	77.8	6.4	3,514	50.1	49.9	0
6 Chem-Resistant coveralls + Gloves + Faceshield	95.3	82.7	27.3	2,732	64.5	35.5	0

* Deposition to outside of coveralls + hand + head exposure (torso patch estimate).
† Deposition beneath coveralls (mean of cotton and Sontara) + hand + head exposure.
‡ Gloves reduced exposure from 13,182 to 1,762 μg/hr.
§ Assumes faceshield protects 44.7% of head.
# Assumes chemical-resistant coveralls replace cotton or Sontara and provide 100% protection.

faceshields would provide greater exposure reduction under these conditions than would further efforts to provide truly chemical resistant coveralls. By implication, use of hoods would also be likely to provide more protection than improved coveralls. The final scenario (S-6) indicates use of faceshields and improved coveralls would reduce exposure by 27% when compared with the label-required PPE used in this study.

Discussion

These studies have demonstrated that coverall garments similar to those used routinely by pesticide applicators did not provide the levels of protection expected. No significant improvement in protection occurred when nonwoven garments were substituted for traditional woven garments. Indeed the nonwoven garments suffered from the most serious flaws in design and provided little, if any, increased resistance to chemical penetration. The use of fluorescent tracers and imaging analysis clearly documented substantial exposure to the arms of workers wearing garments with large sleeve openings. When this design failure was rectified, little exposure could be detected on the protected body. It appears that the strength of the tracer/imaging analysis lies in measuring exposures occurring under, rather than through, garments and in detecting exposures that otherwise would have been undocumented by the patch technique. The use of patches to detect fabric penetration was far more sensitive than was tracer/imaging analysis. Low levels of tracer on skin were difficult to quantify by imaging, whereas chemical analysis of patch extracts detected <10 ng/cm^2. The techniques thus served complementary functions in documenting the limitations of chemical protective clothing performance.

Analysis of exposure distribution revealed that further improvements in protective coveralls would do little to reduce total dermal exposure of applicators under the field conditions tested. Proper use of such personal protective equipment as gloves and faceshields could reduce exposure more than chemically resistant coveralls. It should be noted that hand exposure may have been even higher than the values reported here. Recent studies in our laboratory indicated that only about 30% of the organophosphorus insecticide, chlorpyrifos, in a liquid formulation, was removed from hands by the ethanol handwash procedure used in this study. Further efforts should be directed at establishing accurate hand exposure assessments methods.

The findings of this study are consistent with those of an earlier study of protective clothing performance during airblast applications. The most important finding of the earlier study concerned the role of CPC in exacerbating heat stress; this was confirmed by our observations. Use of such garments during high temperature, high humidity conditions places an excessive and potentially dangerous burden on workers. Label requirements for CPC must be qualified by limits on environmental parameters related to heat stress to strike a proper balance between protection and comfort.

Conclusions

Exposure beneath CPC occurred due to both design failures and fabric penetration. None of the test garments can be considered chemically resistant under the field conditions evaluated in this study. Properly designed garments (woven or nonwoven) such as those evaluated in this study provide a substantial reduction in exposure when compared with a theoretical "unprotected" worker, but improvement in the chemical resistance of coverall garments will reduce further exposure only a small amount. Faceshields could provide approximately three more times the exposure reduction than would result from improved coverall garments. The hands, even when protected by chemical resistant gloves, contribute a substantial proportion of total dermal exposure, as does the unprotected face/head region. The use of fluorescent tracers and video imaging analysis allows measurement of exposure that occurs by pathways that the patch technique would be unlikely to detect or inaccurately quantify (e.g., exposure through openings in garments). The patch technique was far more sensitive in detecting fabric penetration. The techniques appear to play complementary roles in documenting the performance of CPC under realistic field conditions.

Recommendations

Dermal and respiratory exposures under the work conditions studied are relatively high for pesticide applicators. Workers conducting airblast applications would be better protected by closed cab systems or any other technology that places a well-defined barrier between the worker and the pesticide spray. PPE requirements should consider the potential for heat stress and should be designed to strike a balance between protection and comfort. Conditions under which PPE is not to be used should be defined and enforced to reduce the risk of illness related to heat stress. Implementation of PPE requirements or recommendations should include procedures whereby employers and workers receive appropriate and ongoing education and training regarding PPE use. Important factors to be considered in developing PPE requirements or recommendations include:

- Woven or nonwoven coveralls similar to those tested in this study provide substantial protection to most of the body; improvements in the chemical resistance of such garments will probably not reduce total dermal exposure significantly;
- The hands, even when chemical resistant gloves are worn, contribute a substantial proportion of total dermal exposure under the use conditions studied. Further reduction in hand exposure will be achieved only by more effective employer and worker education and training;
- The unprotected head represents a substantial proportion of total dermal exposure;
- Use of a hood covering the back of the neck and most of the head would reduce exposure significantly and addition of a faceshield would further reduce exposure;
- Protective garments designed and marketed for use by pesticide applicators should be field tested to determine performance. Traditional laboratory tests (e.g., permeability testing) cannot characterize effects of garment design and appear to be inadequate measures of potential chemical breakthrough.
- Users should be provided with accurate information regarding garments designed and marketed for pesticide handlers. Claims regarding the ability of garments to protect workers should be accurate. In particular, garments should not be referred to as "chemical resistant" or "liquid proof" unless these qualities have been demonstrated under realistic field use conditions.

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The complete report, entitled "Fluorescent Tracer Evaluation of Protective Clothing Performance," (Order No. PB94-100 146/AS; Cost: $19.50, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
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