CHAPTER 6.6

ERGONOMIC FACTORS IN CHEMICAL HAZARD CONTROL

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6.6.1 INTRODUCTION

The application of ergonomics or human factors to occupational toxicology (Johnson, 1983) and to the control of chemical exposures would appear to have been more incidental than planned. This premise is based on our inability to find a body of information in the literature that would provide those responsible for controlling chemical exposure with human-factors guidelines with which to work. Konz (1979), in his book *Work Design,* includes an excellent review chapter on toxicology, but brings no application of human factors to control of the toxic hazards; instead, control techniques, exclusive of the worker, that are common to the industrial hygiene literature are reiterated. This exclusion of the worker from control strategies seems to have its base half a century ago in the writings of two eminent occupational physicians: Legge, the first Medical Inspector of Factories, Great Britain, and Hamilton of the United States. Legge (1934) wrote:

> (*1*) *Unless and until the employer has done everything—and everything means a good deal—the workman can do next to nothing to protect himself, although he is naturally willing enough to do his share.*
>
> (*2*) *If you can bring an influence to bear external to the workman (i.e., one over which he can exercise no control) you will be successful; and if you cannot or do not, you will never be wholly successful.*"

Legge provided some examples of the kinds of external influences he had in mind—substitution of innocuous substances for toxic ones, performance of operations in closed systems, and local ventilation. Examples of controls he enumerated as being not completely effective (because they involve human factors) included respirators, gloves, goggles, and washing conveniences.

Hamilton (1934) wrote that prevention of industrial poisoning is primarily the task of the engineer and that it must never be forgotten that the great majority of the industrial poisons enter the body with the inspired air, and therefore the preventive measures must be planned with a view to keeping the air of the workshop free from poison. She then briefly summarized the preventive measures as follows:

1. Prevent formation or escape of gases, fumes, and dust.
2. If (1) is impossible, remove by means of exhausts.
3. If (2) is impossible, dilute as much as possible by abundant ventilation and by fans blowing air past the face of the worker.
4. If all these are impracticable, protect the worker by a filter mask, absorbent gas mask, or positive pressure air mask.
5. If all the above measures are impracticable, select workers with proved resistance to the poison and put them on short work shifts.
6. For poisons that enter through the skin, prevent escape of fumes and dusts and prevent spilling of liquids.
7. Maintain scrupulous cleanliness of benches, apparatus, and so forth.
8. Provide and launder washable working clothes.
9. For all, provide adequate washing facilities and a clean lunchroom. Workers with poisons that enter through the skin and workers exposed to excessive dust in the air should have shower baths provided, with hot water, soap, and towels.

The control methods advocated by these authors have become the theme in most industrial hygiene literature and the major basis of controlling the hazards of toxic chemicals. Thus Schilling and Hall (1973), Peterson (1977), and Olishifski (1979) discuss control of chemical hazards in terms of substitution, total enclosure, locally applied exhaust ventilation, dust suppression, segregation of processes, general ventilation, general cleanliness, personal hygiene, personal protection, and education, in approximate descending order of preference.

Historically, then, the control of chemical hazards has been placed in the hands of engineers charged primarily with preventing inhalation by enclosure and by ventilation, methods that are commendable because they do "bring influences to bear external to the workman" as Legge advocated.

These methods, which usually involve large capital outlays, are most applicable to routine operations, and thus their application is common to factories, but there remain many chemical exposures that are inadequately controlled because ergonomists and human-factors engineers have not been involved. In this chapter we identify human factors that are important to occupational toxicology, and provide suggestions and examples of how they can be applied to preventing occupational disease.

6.6.2 OCCUPATIONAL TOXICOLOGY AND HUMAN FACTORS

For a toxic substance to have an effect, it must come in contact with the body in sufficient amount and for sufficient time either to affect the tissues it contacts directly or to be absorbed into the body where it can have general, systemic toxic effects.

Because toxic substances first contact the outside of the body we first discuss the effects of contact on the surfaces and then absorption across these surfaces and suggest roles for ergonomists and human-factors engineers in intervention. The outside of the body includes the skin, nails, eyes, teeth, oral passages, nasal passages, upper airways, lungs, and digestive tract. Each of these structures has a history of being affected by exposure to toxic substances in solid, liquid, aerosolized, or gaseous form.

6.6.2.1 Effects of Toxicants on the Skin, Eyes, and Oral Structures

Skin diseases are the most frequently occurring of all occupational diseases. Because the skin is the major area of the body in direct contact with the environment, it is subjected to chemicals in all forms—gases, liquids, and solids present in the air and on tools and working surfaces, in addition to those that workers handle directly. As a result of this substantial body contact, chemical exposures contribute significantly to the totality of occupational skin disorders.

The skin may suffer damage from a variety of substances, including acids, alkalis, halogens, and others. It is damaged as fat solvents remove protective oils; abraded by fibers, metals, and dusts; allergenically sensitized by numerous and diverse substances; and dehydrated. Some substances are keratogenic and carcinogenic to the skin. The hands, including the nails, are particularly vulnerable when they are used as tools, especially by artisans, craftsmen, repairmen, and many others who take advantage of their sense of touch and maneuverability.

Ergonomists and human-factors engineers can play a substantial role in the reduction or elimination of effects of chemicals on the skin through design of jobs, tools, and protective materials (clothing, gloves, and creams) to be used by workers.

Eyes are affected directly by chemical substances that are present in the air as well as by those liquids and solids that get directly into the eye. Substances in the air are often irritating to the eye, and this irritation may serve as a useful indicator or warning to the worker of the presence of substances in the air. Eye irritation has served as the basis for limiting the concentration of many substances in the work environment. Eye irritants, if present at high enough concentration or for sufficient duration, cause tearing and impair vision. The eye is another important tool that the worker uses, and this use places the eye in many vulnerable situations. Human-factors engineers have a large role to play in designing work stations, jobs, and equipment that will reduce the vulnerability of the eye to chemical hazards. Two other areas where human-factors technology can be brought to bear are in the design of protective eyewear and in promoting its use.

The mouth and its parts, including the teeth, have also been used as tools, for example, in pipetting, licking stamps and envelopes, wetting the fingers for turning pages, holding nails, and biting threads, and in this capacity have been exposed to toxic substances. Toxic substances inhaled through the mouth may be dissolved in saliva and mucus, and particulate material may be deposited on the surfaces. Teeth have been directly affected by contact with dusts, acids, and alkalis while breathing through the mouth and while talking, an important occupational activity that has relevance to respirator usage.

6.6.2.2 Effects of Toxicants on Respiratory Passages and Lungs

During normal breathing, most air, 2 to 25 l/min, that enters the body passes through the nasal passages where large particles are deposited, resulting in such effects as nasal cancers in workers exposed to dust in nickel refining, and ulceration and perforation of the nasal septum with exposure to dusts containing mercury, arsenic, and chromium.

Air entering the nasal passages also brings into play the sense of smell, which has been used as a tool to identify chemicals, and can be useful for warning the worker of impending danger for many toxic substances. It is well to note, though, that adaptation, or fatigue, occurs and perception of odors disappears during continuous exposures to certain substances. A consequence of some chronic chemical exposures is permanently diminished or lost sense of smell.

Very reactive chemicals such as ozone, formaldehyde, and chlorine are irritating to the nasal mucosa, and this irritating property can serve as a basis for limiting exposure concentrations as well as warning the worker of impending hazards. Other manifestations of exposure of the nasal passages include tissue congestion, inflammation, and nasal discharge.

The upper airways, trachea, bronchi, and lungs suffer a number of effects from toxic chemicals and dusts, including smooth muscle responses to irritants, sensitization with asthmatic response, chronic bronchitis, emphysema, cancer, and a variety of agent-specific diseases such as silicosis (silica in the lung), asbestosis, and byssinosis (cotton dust in the lung), all of which compromise respiratory function. For example, silicosis and asbestosis induce inflammation, fibrosis, and scarring, thereby reducing elastic properties of the lung and, in many cases, gas exchange.

Under many conditions of work the only way, other than removing the worker from the workplace, to diminish or prevent inhalation of toxic substances is by the use of respirators. Many ergonomic and human-factors issues become involved—comfort, visibility, loss of sense of smell (e.g., an odorless environment), maneuverability (particularly with air-line and self-contained breathing apparatuses), facial characteristics, appearance, perception of need, increased work of breathing, and with self-contained breathing devices, increased work of carrying the device.

6.6.2.3 Effects of Toxicants on Internal Organs

Toxic effects involving the internal organs and tissues occur after absorption of the chemical substance into the body tissue and their magnitude is usually proportional to the absorbed dose. Thus prevention of absorption is the key to eliminating all such effects. Rather than summarizing toxic effects, we present what is known about absorption of toxic substances and suggest ways that this information can be used for ergonomic and human-factors intervention.

6.6.3 Human Factors and Absorption of Toxic Substances

Absorption occurs across all membranes, but at different rates, these rates depending on the anatomy of the membrane, whether active transport is present or not, and upon characteristics, such as solubility and volatility, of the substance being absorbed. In general, the lungs, with about 70 m^2 of surface area, and the gastrointestinal tract, with about 10 m^2 of surface area, are anatomically and physiologically adapted to absorption, whereas the skin, with a surface area of about 2 m^2, is not.

The lungs have a history of being considered as the major site for absorption of toxic chemicals by workers. Consequently more information on occupational toxicology is based on inhalation than on other routes of absorption; for this reason absorption from the lungs must serve as the standard for evaluating absorption from the skin and the digestive tract.

6.6.3.1 Factors Associated with Absorption from the Lungs

The amount of toxic substance that can be absorbed from the lungs is related to the concentration of that substance in the inhaled air and to the volume of air breathed. Concentrations of substances in the air of workplaces are usually expressed in parts per million (ppm) or milligrams per cubic meter (mg/m^3); in this chapter, the latter is used. In the United States and many other countries, the major source of information on acceptable concentrations of substances in workroom air is the American Conference of Governmental Industrial Hygienists (ACGIH). For nearly 50 years, that organization has been recommending Threshold Limit Values for substances in workroom air (TLVs®). Currently there are TLVs for over 600 chemical substances (ACGIH, 1984). The TLVs are the 8 hr time-weighted average concentrations that will protect nearly all people exposed. For many substances, there is also a short-term exposure limit (STEL), which is the 15 min time-weighted average exposure that should not be exceeded at any time during a work day; exposures at the STEL should not be repeated more than four times a day, with at least 60 min between exposure periods. For about three dozen substances, a "ceiling limit," which should not be exceeded even instantaneously, is recommended instead of a TLV or STEL. The TLVs range from 0.00006 mg/m^3 for proteolytic enzymes to 9000 mg/m^3 for carbon dioxide, with the majority in the range of 0.1 to 10 mg/m^3 (Table 6.6.1).

Table 6.6.1 summarizes the TLV's (in mg/m^3 ranges) and provides some interpretation of these for moderate and heavy work in terms of the amounts that would be available over a workday for absorption by the lungs. Approximate equivalent volumes for liquid materials are presented in metric units which are referred to units that may be more easily visualized by some readers.

The important point is that, for all substances with TLV's less than 1000 mg/m^3, the permissible daily dose is not large (less than 2 tablespoons), and for the more toxic substances, those below 1 mg/m^3, it is very small (less than 1 drop). It is also well to keep in mind that these amounts represent what might be presented to the lungs for absorption and that the amount absorbed may be substantially less (Table 6.6.2).

Table 6.6.2 presents experimental data obtained from human subjects exposed for 30 min to solvent vapors at various concentrations and at various workloads. The exposure concentration is expressed in milligrams per cubic meter; the amounts of vapor presented to the lung (inhaled) and absorbed are expressed in milligrams. It is worth noting the proportionality of the amount of substance absorbed to the level of work (air breathed) and to the concentration of substance in the air. Thus for xylene, doubling the concentration doubles the amount absorbed; and increasing the air breathed fivefold

Table 6.6.1 Summary of TLVs and Potential for Daily Absorption from the Lung at Light and Heavy Work

		Potential for Absorption/Day			
		Light Work, 8 Hr		Heavy Work, 10 Hr	
TLV Range (mg/m³)	Number of Substances	Weight	Volume[a]	Weight	Volume[a]
≤0.1	59	1 mg	1 μl	3 mg	3 μl
≤1	129	10 mg	10 μl	30 mg	30 μl
≤10	162	100 mg	100 μl	300 mg	300 μl
≤100	88	1 g	1 ml	3 g	3 ml
≤1000	82	10 g	10 ml	30 g	30 ml
≤10000	37	100 g	100 ml	300 g	300 ml

[a] Volume at specific gravity of 1.0. The specific gravities of most of the liquid substances in the TLV list are less than 1.5 and range from 0.61 for pentaborane to 3.11 for bromine; for the more dense liquids, the equivalent volumes would be ½ to ¼ of those listed, and for the least dense ones about 1.5 times those listed. For comparison, 1 drop is about 50 μl; 1 tsp is about 5 ml; 1 tbls is about 15 ml.

increases the amount absorbed fivefold. An example of how the generalizations made in Table 6.6.1 can be applied when specific data (Table 6.6.2) are not available can be demonstrated with butyl alcohol exposure of 300 mg/m³ at light work and at heavy work.

Because the data in Table 6.6.2 are for 30 min exposures they must be multiplied by 16 for an 8 hr day and by 20 for a 10 hr day. Thus 16 × 220 mg gives about 3.5 g inhaled, compared to the generalization (Table 6.6.1) of 3 g for light work over an 8 hr day; 460 mg × 20 gives about 9.2 g inhaled at heavy work for 10 hr compared to the generalization in Table 6.6.1 of 9 g. About 40% of the inhaled butyl alcohol was absorbed, indicating daily doses of about 1.5 and 3.5 g (¼ to ½ teaspoon) at light and heavy work, respectively.

The information provided in Tables 6.6.1 and 6.6.2 provides a basis for ergonomists and human-factors engineers to enter into the field of controlling toxic occupational hazards. First, these data show that measuring only the concentration in the inhaled air does not provide all the information necessary for evaluating a toxic hazard. Measures of work and of the volume of air breathed may be equally important. Second, the data suggest that there may be many opportunities where evaluating the work situation and redesigning the job could reduce the amount of toxic substance absorbed by as much as would be accomplished by more costly, traditional control techniques that would more than halve the time-weighted average exposure. An example would be installation of conveyer belts to eliminate carrying jobs.

6.6.3.2 Factors Associated with Percutaneous Absorption of Liquids

Absorption of toxic substances through the skin (percutaneous absorption) is recognized by the ACGIH (1984) by attaching a "Skin" notation to the TLV for those substances for which there is "potential contribution to the overall exposure by the cutaneous route, including mucous membranes and eyes, either by airborne, or more particularly, by direct contact with the substance." About 150 substances have the "Skin" notation; most of these substances are liquids, about a third are solids, and a small number are gases (ACGIH, 1980).

The reason for assigning the "Skin" notation to the TLVs is not stated by ACGIH (1980) in about a third of the cases, is based on the LD_{50} (dose that will kill 50% of the animals) for rats or rabbits for another third, and is based on other animal data (sensitization; chronic effects) or human experience (experimental or occupational) for the remainder. Another list, the *Registry of Toxic Effects of Chemical Substances* (Tatken and Lewis, 1983) contains over 1600 substances with an LD_{50} from skin application. Many of these may not be included in the TLV list because they do not have significant industrial use, or the LD_{50} may be so high (several grams per kilogram) as to not pose a significant health hazard from skin absorption. Although quantitative data on rates of absorption of liquids and solids applied to the skin of human subjects would be useful as a basis for assigning the skin notation to TLV's and for evaluating occupational skin exposure, they are sparse (Table 6.6.3).

The area of skin most likely to be exposed in work situations is the hands (about 500 cm² each), although in some operations, and especially in accidents, other and larger areas such as the abdomen and legs become exposed. The absorption rates listed in Table 6.6.4 are mostly for the forearm or

Table 6.6.2 Amounts of Various Chemicals Inhaled (I) and Absorbed (A) During 30 Minutes, at Different Work Levels

	Work and Breathing Level[a]									
	Exposure	Rest 10 l/min		Light 25 l/min		Medium 38 l/min		Heavy 54 l/min		
Substance	(mg/m³)	I (mg)	A (mg)	I (mg)	A (mg)	I (mg)	A (mg)	I (mg)	A (mg)	Source
Acetone	740	[261]	115	[495]	228	[737]	339	[1024]	471	Astrand, 1983
Butyl alcohol	300	90	43	220	81	326	130	460	193	Astrand, Ovrum, Lindqvest, and Hultengren, 1976
	600	171	78	406	159					
n-Hexane	360	[105]	[25]	[302]	[47]					Veulemans, van Vlem, Tanssens, Masschelein, and Leplat, 1982
	720	[225]	[48]							
Methyl alcohol	250	[80]	[45]							Sedivec, Mraz, and Flek, 1981
	300	[105]	[58]							
Methylene chloride	870	241	132	676	300					Astrand, Ovrum, and Carlsson, 1975
	1740	479	275	1270	565	1996	574	2781	637	
Styrene	210	57	39	146	95	229	145	355	210	Astrand, 1983
	630	232	140							Astrand, Kilbom, Ovrum, Wahlberg, and Vesterberg, 1974
	1050	374	235							
	1470	503	309							
Toluene	300	93	48	219	107	351	142	517	152	Carlsson, 1982
	375	[100]	72	[300]	174	[450]	228	[650]	277	Carlsson and Lindqvist, 1977
Trichlorethylene	540	155	81	390	179					Astrand and Ovrum, 1976
	1080	322	186	749	378	1164	418	1672	419	
White spirit	1000	293	179							Astrand, Kilbom, and Ovrum, 1975
	1250	321	195	880	357					
	1500	371	182							
	2000	522	252							
	2500	540	344	1690	816					
Xylene	435	126	79	343	219	516	301	762	392	Astrand, Engstrom, and Ovrum, 1978
	870	242	166	618	407					

[a] Brackets indicate calculations from data in the source cited.

Table 6.6.3 Absorption Rates of Liquids through Skin of Human Subjects

Substance	Absorption Rate ($\mu g/cm^2 \cdot min$)	Source
Aniline		
In water, 10 g/l	5	Baranowska-Dutkiewicz, 1982
In water, 20 g/l	20	
Aniline	50	Baranowska-Dutkiewicz, 1982
	5	Piotrowski, 1957
Benzene	7	Hanke, Dutkiewicz, and Piotrowski, 1961
	150	Baranowska-Dutkiewicz, 1982
Carbon disulfide	150	Baranowska-Dutkiewicz, 1982
Ethyl benzene	466	Dutkiewicz and Tyras, 1969
Ethylene glycol dinitrate	7	Gross, Kiese, and Resag, 1960
Methyl alcohol	200	Dutkiewicz, Konczalik, and Karwacki, 1980
Methyl *n*-butyl ketone	6	Divincenzo, Hamilton, Kaplan, Krasavage, and O'Donoghue, 1978
Phenol		
In water; 2.5 g/l	1	Baranowska-Dutkiewicz, 1981
In water; 5.0 g/l	3	
In water; 10.0 g/l	5	
Styrene	200	Dutkiewicz and Tyras, 1969
Toluene	300	Dutkiewicz and Tyras, 1969
Xylene	100	Dutkiewicz and Tyras, 1969
m-Xylene	2	Engstrom, Husman, and Riihimaki, 1977

the entire hand. As reported by Maibach, Feldmann, Milby, and Serat (1971) and Guy and Maibach (1984), these rates are likely to be lower than for other parts of the body, on the average about half. In addition to absorption rates being different for different parts of the body, absorption rates can be tremendously increased (200-fold) for damaged skin (Ilyin, Ivannikov, Parfenov, and Stolyarov, 1975).

Thus estimating the dose of toxicant that may be absorbed from skin exposure requires an evaluation of the rate at which the chemical may be absorbed; the area and type of skin involved, and its integrity; duration of the exposure; and volatility of the material. Duration of exposure and volatility of the compound must be considered together; volatile compounds such as benzene (vapor pressure at 20°C = 75 mm Hg) evaporate from exposed skin in minutes after a splash or removal of the hands from the liquid, whereas less volatile compounds, such as ethylene glycol dinitrate (vapor pressure at 20°C = 0.05 mm Hg), remain on the skin until absorbed or washed off. Thus estimates of the duration of exposure, or time during which absorption can occur, include observed duration of contact with the liquid plus an estimate of the residual contact time after cessation of the observed contact. The amount of residual material remaining on the skin, for example, after removal of the hands from a solution will be quite different for different materials depending on their physical characteristics; immediately after removal of a hand from a beaker of water or ethanol as much as 4 mg/cm² may remain on the hand, whereas with light paraffin oil, about twice this much will remain.

As an example of how the data presented in Tables 6.6.1 to 6.6.3 can be utilized to evaluate a

Table 6.6.4 Liquid Contact ($cm^2 \cdot min$) Required to Absorb Daily Doses Implied by the TLV at Light Work[a]

Absorption Rate ($\mu g/cm^2 \cdot min$)	TLV (mg/m^3)				
	0.1	1.0	10	100	1000
1	600	6000	60,000	600,000	
10	60	600	6,000	60,000	600,000
100	6	60	600	6,000	60,000
1000	0.6	6	60	600	6,000

[a] Assumes 50% of amount inhaled is absorbed.

skin exposure problem, let us take the case of methyl alcohol, a solvent likely to be present in preparations for removing paint.

Methyl alcohol is one of the substances with the "Skin" notation, and it has a TLV of 260 mg/m^3 (ACGIH, 1984). According to Table 6.6.1 it would fall in the TLV range ≤ 1000, which indicates the potential for respiratory absorption during 8 hr at light work at the TLV would be (by linear extrapolation) 2.6 g (or approximately 2.6 ml). Because the data in Table 6.6.2 suggest that, in general, about half of this actually would be absorbed, a reasonable expected daily dose suggested by the TLV would be about 1.3 g; also some data are available in Table 6.6.2 on methyl alcohol absorption at rest to refine this estimate of expected daily dose. If the 45 mg listed for absorption during 30 min is extended linearly to 8 hr, the absorbed dose would be 720 mg which, when multiplied by 2 for correction to light work (which the absorption data in Table 6.6.2 suggest is reasonable), gives 1.4 g compared to the rougher estimate of 1.3 g for the allowable daily dose. The information available in Table 6.6.3 on the rate of absorption of methyl alcohol through the skin is about 200 μg/cm$^2 \cdot$ min.

If we divide 1.3 g by 200 μg/cm$^2 \cdot$ min we find that 6500 cm$^2 \cdot$ min of exposure, or one hand submerged in methyl alcohol for 13 min, would be equivalent to working all day in an atmosphere containing methyl alcohol at its TLV. Generalizing the logic of this example and assuming the allowable daily absorbed dose of a toxicant is half that inhaled at light work at the TLV for 8 hr, Table 6.6.4 was constructed, which gives the cm$^2 \cdot$ min of exposure of the skin to liquids that would result in percutaneous absorption of the daily dose so implied by the TLV. The first entry in Table 6.6.4 was calculated as follows:

If the TLV is 0.1 mg/m^3, the respiration rate at light work is 25 l/min = 0.025 m^3/min, the workday is 8 hr = 480 min, and the amount absorbed is half that inhaled (0.5)

Then the absorbed dose is
$0.1 \times 0.025 \times 480 \times 0.5 = 0.6$ mg $= 600$ μg

If the absorption rate is 1 μg/cm$^2 \cdot$ min

Then the cm$^2 \cdot$ min of skin exposure required to absorb that dose is
$600/1 = 600$ cm$^2 \cdot$ min

For order of magnitude interpretations of Table 6.6.4, consider that the area of a thumb is about 15 cm^2, a hand, about 500 cm^2, and the whole body, about 20,000 cm^2; then 60 cm$^2 \cdot$ min is equivalent to holding the thumb in liquid for 4 min; 600 and 6000 cm$^2 \cdot$ min are about equal to holding the hand in liquid for 1 and 10 min, respectively; the highest value tabulated in Table 6.6.4, 600,000 cm$^2 \cdot$ min, would be equivalent to whole-body immersion for 30 min, an unlikely situation, but one that might be approached by soaked clothing from a large spill if the clothes were not removed.

Prevention of absorption of liquids through the skin can be accomplished by redesigning equipment and jobs to eliminate the exposure and by providing effective barriers. Coletta, Schwope, Arons, King, and Sivak (1978); Mikatavage, Que Hee, and Ayer (1984); and Stamper, McLeod, Betts, Martinez, and Barardinelli (1984a, 1984b) reported on laboratory evaluations of protective clothing materials for resistance to chemicals. Einert, Adams, Crothers, Moore, and Ottoboni (1963); Guillemin, Murset, Lob, and Riquez (1974); Lauwerys, Dath, Lachapêlle, Buchet, and Roels (1978); Lauwerys et al. (1980); Ishihara, Kanaya, and Ikeda (1976); Hogstedt and Stahl (1980); Fukuchi (1981); and Maxfield, Barnes, Azar, and Trowchimowicz (1975) give information on effectiveness of gloves and barrier creams in laboratory and workplace exposures.

6.6.3.3 Factors Associated with Percutaneous Absorption of Solids

Quantitative data on absorption rates of solid materials applied to the skin were not found, even though about 50 solid substances are included among the TLVs with the "Skin" notation. However, information on amounts of material deposited on the skin of workers is available (Table 6.6.5). In the study of lead arsenate exposure (Wojeck, Nigg, Bramen, Stamper, and Rouseff, 1982), the skin contamination was reported in units of micrograms per square centimeter; when about 20,000 cm^2 of body surface was involved, the total whole-body contamination was up to 1200 mg for lead arsenate. Because the TLV for lead arsenate is 0.15 mg/m^3 (ACGIH, 1984), the maximum acceptable daily respiratory exposure (at heavy work for 10 hr) would be about 4.5 mg (linear extrapolation from Table 6.6.1); thus if only about 0.03% of the whole-body contamination was absorbed (which could be accomplished over 8 hr at an absorption rate of only 0.0005 μg/cm$^2 \cdot$ min), the maximum acceptable absorption from the respiratory tract at the TLV would likely be exceeded.

In the studies summarized in Table 6.6.5, inhalation exposure was minimal, usually because respirators were worn, and absorption from skin contamination was demonstrated by analysis of body fluids. It is important to note the relatively low concentrations (50 μg/m^3) found in the air in these studies.

In extremely dusty atmospheres where respirators are commonly worn and concentrations of dusts may be in units of milligrams per cubic meter, whole-body contamination must be several times the

Table 6.6.5 Contamination of the Skin of Workers after Exposure

Substance	Condition of Work	Air Concentration ($\mu g/m^3$)	Duration (hr)	Skin Contamination ($\mu g/cm^2$)	Source
Benzidine	Production	0.8	Workday	3–7	Krajewska, Adamiak-Ziemba, Suwalska, and Koskecka, 1980
Azinphosmethyl	Crop spraying	50	2.5–9	0.01–0.05	Franklin et al., 1981
Lead arsenate	Crop spraying	2–5	10	30–60	Wojeck et al., 1982

worst case condition presented in Table 6.6.5. Thus requirements for clean clothes, showers, and protective clothing are obvious when dusts and aerosols are involved.

6.6.3.4 Factors Associated with Percutaneous Absorption of Vapors and Gases

As pointed out by the ACGIH, few quantitative data are available describing absorption of vapors and gases through the skin, but protection of the respiratory tract, while leaving the rest of the body exposed, particularly to a substance with a low TLV, may present a hazardous situation. Absorption of vapors and gases through the skin depends on the concentration in the air, the area of body surface exposed (usually all of it), the temperature and humidity of the air, and characteristics of the substance being absorbed. The little quantitative information available from experimental exposures of human subjects is presented in Table 6.6.6, along with the concentrations of the substances at the TLV and in saturated air (at 20°C) and an absorption factor calculated by dividing the amount absorbed by the product of exposure time and exposure concentration.

This absorption factor [in units of $\mu g/min \cdot mg/m^3)$] can be used for estimating the doses of gases and vapors absorbed through the skin, if the exposure time and the exposure concentration are known (assuming that the total surface area of the skin is exposed and that, for practical purposes, differences between persons in skin surface area can be ignored). Although the data in Table 6.6.6 for aniline may suggest otherwise, those for nitrobenzene, phenol, and xylene suggest that the absorption factor is independent of substance concentration in the air, which is consistent with the premise that the absorption rate is proportional to the concentration of the substance in air.

If linearity is assumed, then the $min \cdot mg/m^3$ of whole-body exposure to a toxicant while wearing a respirator that might result in absorption of amounts of that toxicant suggested by the TLV can be calculated. Let us take the case of styrene, for which the TLV is 215 mg/m^3. At light work, for an 8 hr exposure at that concentration, a worker might inhale 2580 mg of styrene ($0.025\ m^3/min \times 480\ min \times 215\ mg/m^3$) and absorb about half, or about 1300 mg.

If a worker was working in an area where styrene was in excess of 215 mg/m^3 and wearing a respirator, one might ask "is more protection needed, or how long can the exposure last?" The percutaneous absorption factor for styrene vapor (Table 6.6.6) is 0.1 $\mu g/(min \cdot mg/m^3)$. Dividing 1300 mg = 1,300,000 μg by 0.1 μg, gives 13,000,000 ($min \times mg/m^3$), which could be attained by working in a saturated atmosphere (about 14,000 mg/m^3) for about 16 hr (960 min). The practical conclusion would be that there would be little need for whole-body protection when working with styrene in a saturated atmosphere.

The logic of this example has been used to construct Table 6.6.7, which gives the $min \cdot mg/m^3$ of exposure of the skin that might result in daily doses suggested by the TLVs.

The first entry in Table 6.6.7 was calculated as follows:

If the TLV is 0.1 mg/m^3, the respiration rate at light work is 25 l/min = 0.025 m^3/min, the workday is 8 hr = 480 min, and the amount absorbed is half that inhaled (0.5)

Then the absorbed dose is $0.1 \times 0.025 \times 480 \times 0.5 = 0.6\ mg = 600\ \mu g$

If the whole-body absorption factor is 0.01 $\mu g/(min \cdot mg/m^3)$

Then the $min \cdot mg/m^3$ of skin exposure required to absorb that dose is $600/0.01 = 60,000\ min \cdot mg/m^3$

In Table 6.6.6 a tremendous difference in absorption is noted when phenol, nitrobenzene, and aniline are compared with the other compounds; for the former group, at exposure concentrations of 5 to 30 mg/m^3, similar amounts are absorbed as with the remaining substances at 1000 to 4000 mg/m^3.

The experimentally absorbed doses of aniline at 50 mg/m^3 and nitrobenzene at 30 mg/m^3 were in excess of the amounts that might be absorbed due to inhalation during light work at the current TLVs of 18 and 5 mg/m^3, respectively. Although the experimental exposure concentrations outlined

Table 6.6.6 **Vapor Absorption (A) Through the Skin of Human Subjects**

Substance	Exposure (mg/m³ · min)		A (mg)	Absorption Factor μg/(min · mg/m³)	TLV (mg/m³)	Saturated Air (g/m³)	Source
Aniline	5	300	15	10	8	4	Dutkiewicz, 1961
	10	300	20	7			
	20	300	30	5			
	50	300	60	4			
Benzene	1000	420	10	0.02	30		Hanke et al., 1961
Methylchloroform	3300	210	2	0.003	1900	902	Riikimaki and Pfaffli, 1978
Nitrobenzene	5	360	7	4	5	3	Piotrowski, 1967
	10	360	14	4			
	30	360	54	4			
Perchloroethylene	4100	210	48	0.05	335	1000	Riikimaki and Pfaffli, 1978
Phenol	5	360	9	5	19	2	Piotrowski, 1971
	9	360	14	4			
	25	360	47	5			
Styrene	2500	210	60	0.1	215	36	Riikimaki and Pfaffli, 1978
Toluene	2300	210	26	0.05	375	148	Riikimaki and Pfaffli, 1978
Xylene	1300	210	21	0.08	435	555	Rikkimaki and Pfaffli, 1978
	2600	210	44	0.08			

Table 6.6.7 Gas or Vapor Contact (Min·mg/m³) with Whole-Body Skin Surface (2 m²) Required to Absorb Daily Doses Implied by the TLV at Light Work[a]

Absorption Factor [g/(min·mg/m³)]	TLV (mg/m³) 0.1	1.0	10	100	1000
0.01	60,000	600,000	6,000,000[b]		
0.1	6,000	60,000	600,000	6,000,000	
1	600	6,000	60,000	600,000	6,000,000
10	60	600	6,000	60,000	600,000

[a] Assumes 50% of amount inhaled is absorbed.

[b] 15,000 mg/m³ for 400 min (about 1 day).

in Table 6.6.6 were usually in excess of the current TLV's, they were substantially less than the respective saturated air concentrations, which are also presented in Table 6.6.6, and which workers might encounter in confined spaces.

Tank cars, storage tanks, silos, sewers, and spaces over open containers are examples of confined spaces that gases may completely occupy, displacing all natural air constituents, or in which the air can be saturated with volatile materials. Consequences of inadvertent entry into such spaces, or of failure of protective equipment, include suffocation (insufficient oxygen), anesthesia (inability to escape), and serious acute poisonings.

The kinds of data needed to determine the amount of protection necessary when entry into confined spaces has to be made have been the subject of this section. When whole-body protection is necessary, ergonomic and human-factors considerations include body-heat production and its removal while wearing the protective clothing; added work associated with wearing the protective clothing and respiratory equipment; visibility; durability of the clothing in regard to the job (e.g., susceptibility to damage from mechanical hazards); and compatibility of the equipment with the job to be done, considering such things as needed maneuverability and restriction of movements imparted to the worker by the protective equipment.

Certainly, insignificant percutaneous absorption of gases and vapors cannot be taken for granted and must be seriously considered, along with appropriate whole-body protection, when respirators are the chosen or necessary control method.

6.6.3.5 Factors Associated with Ingestion of Toxicants

The gastrointestinal tract is involved incidentally in occupational toxicity—substances in the workplace may be accidentally, and sometimes intentionally, ingested in large amounts, but the most common sources of ingestion are from materials entering the mouth from dirty hands or from contaminated food and drink, and from swallowing materials brought up from the lungs by ciliary action and coughing. Common industrial hygiene practices used to prevent ingestion of toxic substances include provision of washing facilities, eating places that are isolated and protected from contamination, and requirements that food and beverages not be taken into the workplace, and indirectly by limiting the inhalation of dusts. Aitio, Jarvisalo, Kilunen, Tossavainen, and Vaittinen (1980) demonstrated that ingestion from deposition on the oral structures of particles too large to be inhaled may also be a problem.

Human factors that are involved include the necessity to eat and drink, habits such as use of tobacco, and the natural tendencies to lick the lips and fingers. At mobile and temporary work stations, such as construction sites, particularly building repair sites, road repair sites, and agricultural work sites, constructing facilities to provide protection is an impossible or impractical consideration. In such cases, involvement of the worker is imperative.

The potential hazards from ingestion can be put into perspective by examining daily doses of systemic poisons that can be absorbed under current occupational exposure limits for substances in the air that workers breath.

Examination of the TLVs reveals a limit of 1900 mg/m³ for ethyl alcohol and a limit of 0.41 mg/m³ for disulfoton. If we consider that about 10 m³ of air would be inhaled at light work during a workday and that about half of the amount of each toxic substance inhaled would be absorbed, we see that in the first case, it would be necessary to ingest about 10 ml (1900 mg/m³ × 10 m³ × 0.5 = 9500 mg) to equal the daily dose suggested by the TLV, whereas in the latter case ingestion of only 2 μl (0.41 mg/m³ × 10 m³ × 0.5 = 2 mg) would suffice. With few exceptions, all substances for which there are TLVs lie between these extremes, with the majority in the range representative of absorbed doses of less than 5 drops. Pesticides and many metals and their salts are among the substances that have TLVs of 1 mg/m³ or less.

Thus, although early writers on occupational toxicology did not consider ingestion to be a major concern, the substances about which they wrote were generally of lower toxicity than many of the chemicals in use today, the problem of air contamination was substantially greater then, and the criteria of toxicity were different.

6.6.4 SUMMARY OF OCCUPATIONAL TOXICOLOGY

The preceding sections of this chapter have presented information bearing on the effects of substances contacting body surfaces and the absorption of toxicants. We have described the principal routes by which absorption can occur and provided a basis for evaluating resulting doses. Inhalation of toxicants, contact with the skin, and ingestion were discussed. Factors that influence the amount of material absorbed for each of these three routes were detailed. Of particular importance, in a human-factors sense, is absorption of toxicants through the skin, and data were presented that permit human-factors specialists to estimate the amount of toxicants absorbed percutaneously. These calculations will be useful to those designers charged with the design of personal protective equipment, in particular.

In the course of describing how toxic substances can be absorbed, we cited, or in some instances alluded to, human factors that affect why, how, and to what extent persons are occupationally exposed to toxicants. But nothing is as instructive as examples from actual workplace experience. For this reason, the next section presents case studies selected from the Hazard Evaluation program of the National Institute for Occupational Safety and Health. The examples are given in the form of case studies. Each was selected to illustrate opportunities for human-factors practitioners to control workplace exposures to toxic substances.

6.6.5 CASE STUDIES

The opportunities a human-factors specialist has in preventing, or reducing, workers' exposure to toxic substances are considerable, but are sometimes unrecognized. Some examples, presented here as case reports, from the National Institute for Occupational Safety and Health (NIOSH) portray areas where human factors can reduce toxic exposures. The first two case studies were selected from the NIOSH Health Hazard Evaluation program, an activity conducted under the authority of the Occupational Safety and Health Act of 1970. Section 20(a)(6) of the Act authorizes the Secretary of Health and Human Services, following a written request from any employer or authorized representative of employees, to determine whether any substance normally found in the place of employment has potentially toxic effects in such concentrations as used or found. The third case study was selected from a research project sponsored by NIOSH. Each of these case studies is developed here in terms of the problem that was investigated, how the health hazard evaluation (HHE) or research project was conducted, the findings, and areas where a human-factors specialist could contribute to reducing the hazards being investigated.

6.6.5.1 Case Study of a Hazardous Waste Site

The problem of how to dispose of hazardous waste arrived when the United States moved from an agrarian to an industrial economy. A common method has been to store the wastes in hazardous waste sites. In recent years a great concern has been expressed by the public as to the risk posed by these sites. This public concern has been translated into legislative actions that require government and private industry to clean up chemical waste dumps. The first case study is concerned with this problem. In 1980 the Department of Health, State of New Jersey, requested that NIOSH provide on-site industrial hygiene consultations during the removal of hazardous waste from a commercial facility (Costello and Melius, 1981). A 2-acre site had been placed under state jurisdiction in 1978 to remove approximately 50,000 drums of unknown chemicals from the dump. In April 1980, an explosion and fire among the 40,000 drums remaining at the site attracted national attention and led to the HHE request.

The workers engaged in removing the drums of chemicals wore various kinds of protective clothing and equipment. The kind depended on the nature of their work, but also to some degree on the policy of the particular company they worked for. Self-contained breathing apparatus and acid-resistant suits were required where direct skin contact with liquids from ruptured drums was possible. It must be mentioned that the cleanup work was being conducted during the summer months.

The NIOSH HHE focused on the exposure of cleanup workers to chemicals found at the site. An extensive set of area air samples was collected for analysis, and personal air samples were obtained from workers who volunteered to wear sampling pumps. Personal protective equipment was evaluated in both field and laboratory tests for its protective value. The investigators also evaluated the respiratory protection programs of the various companies conducting the waste removal.

Findings from the area industrial hygiene sampling and personal sampling showed that none of the air samples exceeded workplace permissible exposure concentrations established by the U.S. Occupational Safety and Health Administration. What was evident, however, was the presence of a large number, in excess of 20, of different toxic chemicals at the site, with aluminum, calcium, iron, phosphorus, toluene, and xylene being present in largest amounts. In addition the programs in place for respiratory protection, heat stress abatement, and air monitoring were inadequate. These findings merit elaboration.

From a toxicologic perspective, the finding that concentrations of individual toxicants in the air samples were acceptable must be considered in the context of the multiple exposures, and chronic effects. There is no good way to evaluate the health effects produced by chronic low-level exposures to a variety of substances even when they can be measured. The National Research Council (1980) recommended that additivity of chemical exposures be assumed and that the guidelines of the ACGIH (1984) be followed. Most chronic health effects caused by toxicants are dose dependent. That is, the greater the dose, the more likely there will be a toxic response. Single or infrequent exposures to substances, as a general rule, are more likely to be associated with acute injury or intoxication, and are less likely to result in chronic disease than are repeated exposures. The point that must be stressed is that not much is known concerning the chronic toxicologic effects of exposure to combinations of mixtures of toxicants, as is the case in hazardous waste cleanups. The human-factors specialist must assume these kinds of chemical exposure pose significant risk to workers; protective equipment and work methods should be designed and employed to minimize this risk.

The HHE found some shortcomings in the protective equipment provided to workers. In particular, the respiratory protection provided was in need of improvement. Some respirators didn't work, others worked poorly, some were improperly fitted, and some were improperly adjusted. From a toxicologic concern, a properly fitted, functional respirator is necessary to protect against toxicants in vapor, aerosol, or gaseous form. Although engineering controls (e.g., ventilation systems) are to be preferred over personal protective equipment as a means of preventing health risks, there are clearly some jobs—and hazardous waste cleanup is one of them—for which personal protective equipment is the only feasible method of protecting workers. The design of protective equipment, especially respirators, that affords the wearer with comfortable, nonthreatening protection should be a fertile area for human-factors specialists.

The acid-resistant suits ("moon suits") were a problem during hot weather. Three cases of heat illness occurred. The effect of the impermeable clothing is to increase the temperature within the suit. This raises the wearer's body temperature, which in turn increases heart rate and blood flow to the extremities. Loss of body fluid occurs by way of perspiration and pores in the skin open. This changed physiological state will have profound effects on any toxic exposure, irrespective of the route of exposure. Should any chemical penetrate the protective clothing, it will come into contact with a vastly different skin from that found at lower body temperature.

Perspiration on the skin, if not absorbed by clothing, may increase the absorption of the alien chemical, increased blood flow in the skin enhances the transport of chemicals absorbed through the skin, and the increased heart rate more quickly distributes the toxicant throughout the body. The challenge to the human-factors specialist is to design protective clothing and work regimens that do not add to the risk posed by the work itself.

6.6.5.2 Case Study of a Small Business

The control of workers' exposure to toxic substances is particularly acute in medium- to small-scale companies, which together employ as many as 80% of U.S. workers.

Companies that employ only a few employees often do not possess the resources to provide elaborate engineering control systems or costly personal protective equipment, and their access to information on toxic hazards may be limited, but, in total, they employ a large number of workers. The following HHE case report illustrates one of the more common problems, exposure to solvents, found in many medium- to small-scale companies.

NIOSH was asked in 1983 to conduct an HHE of a company that manufactures valves (Wallingford, 1983). The manufacturing was done by production line assembly and required the dipping of parts into solvent baths to remove grease. There were 28 workers engaged in the assembly work per workshift. The specific health concern was with the exposure of workers to the two solvents used in degreasing operations, isopropanol and 1,1,1-trichloroethane (methylchloroform). Workers' exposure occurred when the parts to be degreased were dipped by hand into the solvent baths.

Acute exposure to high concentrations of isopropanol vapor can cause irritation of the eyes, nose, and throat, headache, drowsiness, and incoordination. Ingestion may cause nausea, vomiting, diarrhea, cramps, gastrointestinal pain, unconsciousness, and death. Chronic exposure to isopropanol liquid may cause drying and cracking of the skin. Acute exposure to high concentrations of 1,1,1-trichloroethane vapor may cause irritation of the eyes, central nervous system depression, headache, dizziness, drowsiness, incoordination, nausea, irregular heart beat, and unconsciousness. prolonged exposure to very high concentrations may be fatal. Chronic exposure to the liquid may cause drying, cracking, and inflammation of the skin.

All the degreasing tanks had hinged lids to help suppress solvent vapors when closed. None of the degreasing operations were provided with local exhaust ventilation. Observation by the investigators of work practices indicated that direct skin contact with the degreasing solvents occurred frequently. Many employees never wore gloves.

Interviews with workers indicated that 25 (89%) had experienced, at least once, symptoms consistent with exposure to the degreasing solvents. Twenty employees (71%) reported they experienced dry, cracked, or inflamed skin as a consequence of contact with the degreasing solvents. Twelve (43%) indicated they had experienced symptoms of central nervous system effects. These reports should be understood in the knowledge that area industrial hygiene measurements did not find solvent vapor concentrations in excess of permissible exposure limits. However, it is likely that considerable skin absorption occurred, especially in view of the cracked skin seen on many workers' hands. This problem of skin absorption of the degreasing solvents was further compounded by the observation that the workers used these same two solvents to clean their hands of grease.

This particular HHE exemplifies the problems faced by a human-factors specialist or industrial hygienist in reducing the workers' exposure to solvents. Owing to the modest size of the company, it is unlikely that a mechanized dipping system to effect degreasing could be installed. No, the human-factors specialist would have to intervene by dealing with what is, not what might be. What are some possibilities?

The most promising avenue is to design more effective hand protection, principally by improving the design of protective gloves. Workers in this company didn't wear the gloves provided by their employer, because they were uncomfortable and ill-fitting. Moreover, the designer of impermeable gloves must ensure that the product does indeed block the passage of the targeted chemicals through the glove materials, a goal that has not always been successful (Hogstedt and Stahl, 1980; Einert, Adams, Crothers, Moore, and Ottoboni, 1963; Ishihara et al., 1976).

Two other recommendations made by the HHE team have toxicologic importance. One recommendation was to cease using the degreasing solvents for cleaning the hands. Hand soap works just as well, but without the hazard posed by the solvents. A second recommendation was to consider the use of water-based degreasers in lieu of the organic-based degreasing solvents. The suggestion to change degreasing compounds exemplifies a general principle of control technology. When possible, substitute a less toxic substance for one with greater toxicity. This principle has relevance to the human-factors specialist who designs protective equipment or engineering control systems. For instance, the chemical composition of protective clothing should be carefully selected in order to avoid placing potentially toxic substances against the skin.

6.6.5.3 Case Study of a Reinforced Plastics Operation

The preceding two case studies were gleaned from the NIOSH HHE program. The third case study was drawn from research performed for NIOSH by the University of Kansas (Hopkins, 1981). Whereas the other case studies drew principally upon recommended changes in technology in order to reduce workers' exposures to toxicants, this case study portrays rather nicely the importance of work practices in controlling these exposures.

The reinforced plastics industry supplies a large quantity and variety of consumer products. The fabrication of these products involves the use of many chemicals, some of which are toxic at sufficiently high exposure levels. Much of the work in this industry is accomplished by hand. For this reason, NIOSH was interested in evaluating the efficacy of prescriptive work practices to reduce workers' exposure to chemicals used in the fabrication of products made from reinforced plastics.

Several small-scale to medium-size companies were visited by the investigators. Manufacturing of reinforced, laminated plastic products, such as those manufactured from styrene-containing resins, typically consists of a series of operations. In brief, a mold coated with wax is sprayed with a mixture of pigmented polyester resin and styrene monomer. A catalyst, such as methyl ethyl ketone peroxide, is mixed with the styrene mixture in the spraying operation. After the mold hardens a reinforcing lamination of fibrous glass is added by spraying a mixture of glass fibers, resin–styrene mixture, and catalyst. Additional layers may be added as needed. In the next operation rollers are used to roll out any gas bubbles trapped in the mixture. A finishing process involves removing the mold, trimming it, and polishing the edges of the hull. A chemical of major concern in this industry is styrene. Styrene monomer in liquid or vapor form is irritating to the eyes, nose, throat, and skin. Repeated contact with the skin may produce a dry, scaly, and fissured dermatitis. Acute exposure to high concentrations may produce symptoms of narcosis, cramps, and death due to depression of the central nervous system. The major metabolite of styrene is mandelic acid in urine.

Following selection of the plants for study, an extensive evaluation commenced of the work practices constituting the fabrication of a variety of consumer products. At the same time, an assessment was conducted of education and training materials and programs relevant to the work practices. The third leg of the triad of research methodologies was the development of motivational methods for workers and supervisors that could be used to ingrain desired work practices.

An early discovery of the investigators was the paucity of empirical data pertaining to the effectiveness of work practices to control toxic exposures. This gap must be filled, another opportunity for human-factors specialists. The specific details of the investigation are too lengthy to present here. A summary will suffice to describe the principles of interest to human-factors specialists.

The plant surveys were conducted by a team of psychologists, industrial hygienists, and human-factors engineers. This team identified a large number of work practices that, if modified, would likely result in reduced exposure of workers to styrene. The work practices can be loosely grouped into two categories, those attendant to housekeeping and those specific to production processes. For the former, 28 improved housekeeping practices were developed. Illustrative examples of them are covering floors in work areas with a disposable material (to prevent an accumulation of styrene resin), keeping the spraying booth filters clean, emptying the waste cans on a more frequent basis, covering the resin and gel-coat containers when not in use, and removing empty chemical containers from the work area.

Some representative examples from the list of 11 modified production work practices are the following: sprayers should always work on the upwind side of any source of airborne styrene; spray, lay up, and roll-out work should be done only in prescribed areas (where exhaust systems were installed); and a spray gun operator should not spray within 6 ft of another person. Training materials, principally in the form of videotapes, describing the recommended work practices were developed. Workers were given training by the investigative team in how to employ the recommended work practices. Tests were administered by the investigators to measure how well the workers understood the desired work practices. If needed, further training was provided. As the workers adopted the revised work practices into their everyday work routine, plant supervisors and select members of the investigative team used expressions of social approval to reinforce the workers' use of the new work practices.

The effectiveness of the work practices recommended by the investigators was dramatic. The reduction in ambient air concentrations of styrene ranged from 50 to 80% varying between individual plants. A corresponding reduction in mandelic acid levels in urine was achieved, ranging from 30 to 60%. There was, therefore, clear evidence that the recommended work practices, when coupled with an effective training program, accompanied by social approval from supervisors and co-workers, led to a pronounced reduction of workers' exposure to, and absorption of, styrene.

The implications of this third case study for human-factors specialists are profound. Simple, in some sense, "obvious" changes in work practices led to a marked reduction in exposure to a toxicant. But to arrive at these recommendations required the exercise of considerable knowledge and personal judgment by the investigators, the workers, and company management. Other kinds of work will require different approaches; this is the challenge presented to human-factors specialists.

6.6.6 HUMAN FACTORS EXPERIENCE FROM HHEs

The three case studies described in Section 6.6.5 exemplify the problems faced by human-factors engineers in reducing or preventing workers' exposure to toxic substances. Protective clothing, if available to workers, often doesn't prevent the toxicants in question from reaching the worker. This results from any number of factors, but chief among the reasons are poorly designed equipment, improperly used equipment, inadequate training in its use, and lack of service and maintenance of the equipment. Each of these factors is amenable to improvement by human-factors specialists.

Human factors stated or implied in other NIOSH HHE reports can be loosely grouped into the following categories:

Inadequate personal protective equipment (e.g., clothing that was permeable to chemicals used by the workers)

Poorly designed work processes (e.g., solvent tanks that require workers to reach into them)

Inadequate appreciation of hazards (e.g., not wearing adequate protective clothing)

Poorly arranged work stations (e.g., positioning work processes so that toxic chemicals are carried between stations)

Absent hygiene facilities (e.g., lack of restrooms or hot showers)

Uninformative engineering controls (e.g., ventilation systems that lack controls that inform how well they are operating)

Each of these categories presents challenging problems to the human-factors engineer toward accomplishing the goal of reducing hazardous exposures.

In Table 6.6.8 are summarized those HHE reports in which human-factors considerations were included in the recommendations. For each HHE cited, we state the condition found at the workplace, the effect of this condition on workers, and the solution proposed by NIOSH investigators to abate the condition.

The problems are particularly difficult where the enterprises involved are medium- to small-scale businesses. We believe the problems to be tractable, however, if existing human-factors knowledge is prudently applied and research is undertaken on ways to solve the more difficult problems of preventing human exposure to toxicants.

Table 6.6.8 Human-Factors Issues Found in NIOSH Health Hazard Evaluations

Source	Findings	Effect	Solution Proposed
Rivera (1975)	Poorly designed solvent bath	Solvent inhalation due to poor worker posture	Redesign the tank
Geissert (1977)	Poorly fitted respirators	Respirators not worn; led to exposure to irritating dust	Implement a training program for use and fit of respirators
Price and Thoburn (1977)	Protective clothing not impermeable	Solvents penetrated the skin	Select impervious clothing from available sources
Gilles (1978)	Engineering process deficient	Workers' hands were dipped into oil	Redesign process to eliminate the hazards
Messite and Fannick (1978)	Manual handling of drugs	Skin and oral exposure of workers	Use an instrument instead of hands
Chrostek (1980)	Manual transport of painted materials	Exposure to paint solvents	Rearrange the work area
Tharr, Murphy, and Mortimer (1982)	Assembly process too far from ventilation	Inhalation of solvent vapors	Revise the work practices and rearrange the work area
Hollett and Klemme (1982)	No protective gloves	Skin absorption of solvents	Provide protective gloves
Chrostek and Elesh (1980)	Loading of drums required reaching into them	Inhalation of toxic dusts	Purchase material in smaller drums or tilt the larger drums
Murphy and Lucas (1982)	Worker had to lean over a mold	Inhalation of off-gassing vapors	Place the sand mold upon a platform; revise work practices
Watanabe, Patnode, Singal, and Ferguson (1982)	Loading of hoppers over workers' heads	Spillage led to drug inhalation	Eliminate overhead scooping by adding a mechanical delivery system
Evans (1978)	Bulky gloves provided for fine work	Gloves not worn; skin exposures	Provide thin-gauge gloves; revise work practices
Williams and Hickey (1983)	Inadequate protective clothing	Skin contact with solvents	Provide ventilation and protective clothing
Ruhe, Watanabe, and Stein (1981)	Control panel too far from degreasing tank	Workers had to go to the tank	Relocate a viewing window so that the tank can be seen
Moran and Love (1980)	No restroom	Technicians couldn't clean chemicals from themselves	Provide bathroom facilities
Kominsky (1979)	Manual inspection of a tank's contents	Inhalation of chemicals	Wear a full-face respirator until an alternate procedure is found
Messite and Fannick (1979)	Photographs coated by hand	Oral ingestion and skin absorption of liquids used	Use swabs to apply the dyes; provide protective finger coverings
McManus and Baker (1981)	Barrier creams used inappropriately	Perspiration increased	Discontinue use of creams
Boxer and Mosely (1983)	Lack of gloves, other equipment	Skin contact with adhesives	Provide pins to hold the parts; provide gloves
Almaguer and Kramkowski (1983)	Dip tank solution too low	Workers splashed solution on themselves	Raise the level of the solution in the tank
Lee (1984)	Portable fans led to air turbulence	Toxic fumes were broadcast	Reposition fans; condition air
Roper and Piccirillo (1976)	Improperly worn dust masks	Dust Inhalation	Use half-face respirators; not dust masks
Burroughs (1976)	Manual handling of metal plates	Cutting oils on workers' skin	Use forceps to handle the parts

REFERENCES

ACGIH (1980). *Documentation of the Threshold Limits Values,* 4th ed. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

ACGIH (1984). *Threshold Limit Values for chemical substances and physical agents in the work environment and biological exposure indices with intended changes for 1984–85.* Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

Aitio, A., Jarvisalo, J., Kiilunen, M., Tossavainen, A., and Vaittinen, P. (1980). Urinary excretion of chromium as an indicator of exposure to trivalent chromium sulphate in leather tanning. *International Archives of Occupational and Environmental Health, 54,* 241–249.

Almaguer, D., and Kramkowski, R. (1983). *NIOSH Health Hazard Evaluation Report HETA 82–116–1319, Modine Manufacturing, McHenry, Illinois.* Springfield, VA: National Technical Information Service No. PB 84–210442.

Astrand, I. (1983). Effect of physical exercise on uptake, distribution and elimination of vapors in man. In V. Fiserova-Bergerova, Ed., *Modeling of inhalation exposure to vapors: Uptake, distribution, and elimination,* Vol. 2, Boca Raton, FL: CRC Press, pp. 107–130.

Astrand, I., and Ovrum, P. (1976). Exposure to trichloroethylene I. Uptake and distribution in man. *Scandinavian Journal of Work, Environment and Health, 4,* 199–211.

Astrand, I., Kilbom, A., Ovrum, P., Wahlberg, I., and Vesterberg, O. (1979). Exposure to styrene I. Concentration in alveolar air and blood at rest and during exercise and metabolism. *Work Environment Health, 11,* 69–85.

Astrand, I., Kilbom, A., and Ovrum, P. (1975). Exposure to white spirit I. Its concentration in alveolar air and blood during rest and exercise. *Scandinavian Journal of Work, Environment and Health, 1,* 15–30.

Astrand, I., Ovrum, P., and Carlsson, A. (1975). Exposure to methylene chloride I. Its concentration in alveolar air and blood during rest and exercise and its metabolism. *Scandinavian Journal of Work, Environment and Health, 1,* 78–94.

Astrand, I., Ovrum, P., Lindqvest, T., and Hultengren, M. (1976). Exposure to butyl alcohol—Uptake and Distribution in man. *Scandinavian Journal of Work, Environment and Health, 3,* 165–175.

Astrand, I., Engstrom, J., and Ovrum, P. (1978). Exposure to xylene and ethylbenzene I. Uptake, distribution, and elimination in man. *Scandinavian Journal of Work, Environment and Health, 4,* 185–194.

Baranowska-Dutkiewicz, B. (1981). Skin absorption of phenol from aqueous solutions in men. *International Archives of Occupational and Environmental Health, 49,* 99–104.

Baranowska-Dutkiewicz, B. (1982). Skin absorption of aniline from aqueous solutions in man. *Toxicology Letters,* 367–372.

Boxer, P. A., and Moseley, C. (1983). *NIOSH Health Hazard Evaluation Report HETA 83-010-1313, Detroit Gasket, Fremont, Ohio.* Springfield, VA: National Technical Information Service No. PB 84-210160.

Burroughs, G. E. (1976). *Health Hazard Evaluation Determination Report No. 75-97-257, C. S. Brainin Company, Mount Vernon, New York.* Cincinnati, OH: National Institute for Occupational Safety and Health.

Carlsson, A. (1982). Exposure to toluene—uptake, distribution and elimination in man. *Scandinavian Journal of Work, Environment and Health, 8,* 43–55.

Carlsson, A., and Lindqvist, T. (1977). Exposure of animals and man to toluene. *Scandinavian Journal of Work, Environment and Health, 3,* 135–143.

Chrostek, W. J. (1980). *Health Hazard Evaluation Determination Report HE 80-108-705, Corporation of Veritas, Philadelphia, Pennsylvania.* Springfield, VA: National Technical Information Service No. PB 81-10644.

Chrostek, W. J., and Elesh, E. (1980). *Health Hazard Evaluation Determination Report HE 79-19-740, Radford Army Ammunition Plant, Hercules Incorporated, Radford, Virginia.* Springfield, VA: National Technical Information Service No. PB 81-170938.

Coletta, G. C., Schwope, A. D., Arons, I. J., King, J. W., and Sivak, A. (1978). *Development of performance criteria for protective clothing used against carcinogenic liquids* (DHEW (NIOSH) Publication No. 79-106). Cincinnati, OH: National Institute for Occupational Safety and Health.

Costello, R., and Melius, J. (1981). *NIOSH Health Hazard Evaluation Report TA 80-77-853, Chemical Control Corporation, Elizabeth, New Jersey.* Springfield, VA: National Technical Information Service No. PB 82-209578.

Divincenzo, G. D., Hamilton, M. L., Kaplan, C. J., Krasavage, W. J., and O'Donoghue, J. L. (1978).

Studies on the respiratory uptake and excretion and the skin absorption of methyl *n*-butyl ketone in humans and dogs. *Toxicology and Applied Pharmacology, 44,* 593–604.

Dutkiewicz, T. (1961). Absorption of aniline vapors in men. In *Proceedings of the 14th International Congress on Occupational Health.* New York: Book Craftsmen Associates, pp. 681–686.

Dutkiewicz, T., and Tyras, H. (1969). Comparative studies on the percutaneous absorption of toluene, ethylbenzene, xylene, and styrene in man (in Polish). *Medycyna Pracy, 20,* (pp. 228–234).

Dutkiewicz, B., Konczalik, J., and Karwacki, W. (1980). Skin absorption and per os administration of methanol in men. *International Archives of Occupational and Environmental Health, 47,* 81–88.

Einert, C., Adams, W., Crothers, R., Moore, H., and Ottoboni, F. (1963). Exposure to mixtures of nitroglycerin and ethylene glycol finitrate. *American Industrial Hygiene Association Journal, 24,* 435–447.

Engstrom, K., Husman, K., and Riihimaki, V. (1977). Percutaneous absorption of *m*-xylene in man. *International Archives of Occupational and Environmental Health, 39,* 181–189.

Evans, W. (1978). *Health Hazard Evaluation Determination Report HE 78-76-548, Western Gear Corporation Flight Structures Division, Jamestown, North Dakota.* Springfield, VA: National Technical Information Service No. PB 81-159443.

Franklin, C. A., Fenske, R. A., Greenhalgh, R., Mathieu, L., Denly, H. V., Leffingwell, J. T., and Spear, R. C. (1981). Correlation of urinary pesticide excretion with estimated dermal contact in the course of occupational exposure to guthion. *Journal of Toxicology and Environmental Health, 7,* 715–731.

Fukuchi, Y., Nitroglycerol concentrations in blood and urine of workers engaged in dynamite production. *International Archives of Occupational Environmental and Health, 48,* 339–346.

Geissert, J. O. (1977). *Health Hazard Evaluation Determination Report No. 75-154-387, Emery Industries, Cincinnati, Ohio.* Springfield, VA: National Technical Information Service No. PB 273821.

Gilles, D. (1978). *Health Hazard Evaluation Determination Report No. 77-88-457, Galion Amco, Inc., Galion, Ohio.* Springfield, VA: National Technical Information Service No. PB 82-194002.

Gross, E., Kiese, M., and Resag, K. (1960). Absorption ethylene glycol dinitrate through the skin (in German). *Archiv fur Toxikologie, 18,* 194–199.

Guillemin, M., Murset, J. C., Lob, M., and Riquez, J. (1974). Simple method to determine the efficiency of a cream used for protection against solvents. *British Journal of Industrial Medicine, 31,* 310–316.

Guy, R. H., and Maiback, H. I. (1984). Correction factors for determining body exposure from forearm percutaneous absorption data. *Journal of Applied Toxicology, 4,* 26–28.

Hamilton, A. (1934). *Industrial toxicology.* New York: Harper Brothers, pp. ix–xix.

Hanke, J., Dutkiewicz, T., and Piotrowski, J. (1961). The absorption of benzene through the skin in man (in Polish). *Medycyna Pracy, 12,* 413–426.

Hogstedt, C., and Stahl, R. (1980). Skin absorption and protective gloves in dynamite work. *American Industrial Hygiene Association Journal, 41,* 367–372.

Hollett, B. A., and Klemme, J. C. (1982). *NIOSH Health Hazard Evaluation Report HETA 81-045C-1217, Uniroyal, Incorporated, Mishawaka, Indiana.* Springfield, VA: National Technical Information Service No. PB 84-183623.

Hopkins, B. L. (1981). *Behavioral procedures for reducing worker exposure to carcinogens (Final Report NIOSH Contract No. 210-77-0040). Cincinnati, OH: National Institute for Occupational Safety and Health.*

Ilyin, L. A., Ivannikov, A. T., Parfenov, Y. D., and Stolyarov, V. P. (1975). Strontium Absorption Through Damaged and Undamaged Human Skin. *Health Physics, 29,* 75–80.

Ishihara, N., Kanaya, A., and Ikeda, M. (1976). *m*-Dinitrobenzene intoxication due to skin absorption. *International Archives of Occupational and Environmental Health, 36,* 161–168.

Johnson, B. L. (1983). Occupational toxicology: NIOSH perspective. *Journal of the American College of Toxicology, 2,* 43–50.

Konz, S. (1979). *Work design.* Columbus, OH: Grid Publishing, pp. 441–428.

Kominsky, J. R. (1979). *Health Hazard Evaluation Determination Report HHE 78-119-637, Texaco, Inc., Bayonne Terminal, Bayonne, New Jersey.* Springfield, VA: National Technical Information Service No. PB 80-163223.

Krajewska, D., Adamiak-Ziemba, J., Suwalska. D., and Kostecka, K. (1980). Evaluation of occupational benzidine exposure of workers in automated benzidine plants (in Polish). *Medycyna Pracy, 31,* 403–410.

Lauwerys, R. R., Dath, T., Lachapelle, J. M., Buchet, J. P., and Roels, H. (1978). The influence of two barrier creams on the percutaneous absorption of *m*-xylene in man. *Journal of Occupational Medicine, 20,* 17–20.

Lauwerys, R. R., Kivits, A., Lhoir, M., Rigolet, P., Houbeau, D., Buchet, J. P., and Roels, H. A. (1980). Biological surveillance of workers exposed to dimethlyformamide and the influence of skin protection on its percutaneous absorption. *International Archives of Occupational and Environmental Health, 45,* 189–203.

Lee, S. A. (1984). *NIOSH Health Hazard Evaluation Report HETA 83-338-1399, Palmer Instruments, Incorporated, Cincinnati, Ohio.* Cincinnati, OH: National Institute for Occupational Safety and Health.

Legge, T. (1934). In S. A. Henry, Ed., *Industrial maladies.* London: Oxford University Press, pp. 2–3.

Maibach, H. I., Feldmann, R. J., Milby, T. H., and Serat, W. F. (1971). Regional variation in percutaneous penetration in man. *Archives of Environmental Health, 23,* 208–211.

Maxfield, M. E., Barnes, J. R., Azar, A., and Trowchimowicz, H. T. (1975). Urinary excretion of metabolite following human exposures to DMF or to DMAC. *Journal of Occupational Medicine, 17,* 506–511.

McManus, K. P., and Baker, E. L. (1981). *NIOSH Health Hazard Evaluation Report HHE 80-084-927, General Electric Company, Lynn, Massachusetts.* Springfield, VA: National Technical Information Service No. PB 83-102848.

Messite, J., and Fannick, N. L. (1978). *Health Hazard Evaluation Determination Report No. 78-6-503, Cumberland Outpatient Department of Beth Israel Hospital, Brooklyn, New York.* Cincinnati, OH: National Institute for Occupational Safety and Health.

Messite, J., and Fannick, N. (1979). *Health Hazard Evaluation Determination Report HE 79-29-566, Giorgi Process, Inc., Yonkers, New York.* Springfield, VA: National Technical Information Service No. PB 81-143778.

Mikatavage, M., Que Hee, S. S., and Ayer, H. E. (1984). Permeation of chlorinated aromatic compounds through Vitron® and nitrile glove materials. *American Industrial Hygiene Association Journal, 45,* 617–621.

Moran, J. M., and Love, J. (1980). *NIOSH Health Hazard Evaluation Report HHE 80-003-785, Steven Janowitz, DDS, Alexandria, Virginia.* Springfield, VA: National Technical Information Service No. PB 82-150152.

Murphy, D. C., and Lucas, C. (1982). *NIOSH Health Hazard Evaluation Report HETA 81-411-1182, Corhart Refractory, Louisville, Kentucky.* Springfield, VA: National Technical Information Service No. PB 84-149885.

National Research Council Panel on Evaluation of Hazards Associated with Maritime Personnel Exposed to Multiple Cargo Vapors (1980). *Principles of Toxicological Interactions Associated with Multiple Chemical Exposures.* Washington, DC: National Acadamy Press.

Olishifski, J. B. (1979). Methods of control. In J. B. Olishifski, Ed., *Fundamentals of industrial hygiene,* 2nd ed. Chicago, IL: National Safety Council, pp. 613–635.

Peterson, J. E. (1977). *Industrial Health.* Englewood Cliffs, NJ: Prentice-Hall, pp. 296–300.

Piotrowski, J. (1957). Quantitative estimation of aniline absorption through the skin in man. *Journal of Hygiene, Epidemiology, Microbiology and Immunology, 1,* 23–32.

Piotrowski, J. (1967). Further investigations on the evaluation of exposure to nitrobenzene. *British Journal of Industrial Medicine, 24,* 60–65.

Piotrowski, J. K. (1971). Evaluation of exposure to phenol: absorption of phenol vapor in the lungs and through the skin and excretion of phenol in urine. *British Journal of Industrial Medicine, 28,* 172–178.

Price, J. H., and Thoburn, T. W. (1977). *Health Hazard Evaluation Determination Report No. 76-60-398, Hayes-Albion Corporation, Wolverine Plastics Division, Milan, Michigan.* Springfield, VA: National Technical Information Service No. PB273749.

Riihimaki, V., and Pfaffli, P. (1978). Percutaneous absorption of solvent vapors in man. *Scandinavian Journal of Work, Environment and Health, 4,* 73–85.

Rivera, R. O. (1975). *Health Hazard Evaluation Determination Report No. 74-135-226 GAF Corporation Equipment Manufacturing Plant, Vestal, New York.* Springfield, VA: National Technical Information Service No. PB 249406.

Roper, C. P., Jr., and Piccirillo, R. E. (1976). *Health Hazard Evaluation Determination Report No. 75-104-325, Olin Corporation, Pisgah Forest, North Carolina.* Springfield, VA: National Technical Information Service No. PB 264806.

Ruhe, R. L., Watanabe, A., and Stein, G. (1981). *NIOSH Health Hazard Evaluation Report HHE*

80-49-808, Superior Tube Company, Collegeville, Pennsylvania. Springfield, VA: National Technical Information Service No. PB 82-232299.

Schilling, R. S. F., and Hall, S. A. (1973). Prevention of occupational disease. In R. S. F. Schilling, Ed., *Occupational health practice.* London: Butterworths, pp. 408–420.

Sedivec, V., Mraz, M., and Flek, J. (1981). Biological monitoring of persons exposed to methanol vapors. *International Archives of Occupational and Environmental Health, 48,* 257–271.

Stampfer, J. F., McLeod, M. J., Betts, M. R., Martinez, A. M., and Barardinelli, S. P. (1984a). Permeation of polychlorinated biphenyls and solutions of these substances through selected protective clothing materials. *American Industrial Hygiene Association Journal, 45,* 634–641.

Stampfer, J. F., McLeod, M. J., Betts, M. R., Martinez, A. M., and Barardinelli, S. P. (1984b). Permeation of eleven protective garment materials by four organic solvents. *American Industrial Hygiene Association Journal, 45,* 642–645.

Tatken, R. L., and Lewis, R. J. (1983). *Registry of toxic effects of chemical substances,* 1981–1982 ed. [DHHS (NIOSH) Publication No. 83-107]. Washington, DC: U.S. National Government Printing Office.

Tharr, D. G., Murphy, D. C., and Mortimer, V. (1982). *NIOSH Health Hazard Evaluation Report HETA 81-455-1229, Red Wing Shoe Company, Red Wing, Minnesota.* Springfield, VA: National Technical Information Service No. PB 84-172592.

Veulemans, H., Van Vlem, E., Janssens, H., Masschelein, R., and Leplat, A. (1982). Experimental human exposures to *n*-hexane—study of the respiratory uptake and elimination, and *n*-hexane concentrations in peripheral venous blood. *International Archives of Occupational and Environmental Health, 49,* 251–263.

Wallingford, K. M. (1983). *NIOSH Health Hazard Evaluation Report HETA 83-170-1346. Xemox Corporation, Cincinnati, Ohio.* Cincinnati, OH: National Institute for Occupational Safety and Health.

Watanabe, A. S., Patnode, R., Singal, M., and Ferguson, R. P. (1982). *NIOSH Health Hazard Evaluation Report HETA 81-322-1228, Mylan Pharmaceuticals, Morgantown, West Virginia.* Springfield, VA: National Technical Information Service No. PB 84-172550.

Williams, T. M., and Hickey, J. L. S. (1983). *NIOSH Health Hazard Evaluation Report HETA 81-311-1250, Uniroyal, Inc., Opelika, Alabama.* Springfield, VA: National Technical Information Service No. PB 84-173038.

Wojeck, G. A., Nigg, H. N., Bramen, R. S., Stamper, J. H., and Rouseff, R. L. (1982). Worker exposure to arsenic in Florida grapefruit spray operations. *Archives of Environmental Contamination and Toxicology, 11,* 661–667.

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