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Aqueous Foam Toxicology Evaluation and Hazard Review

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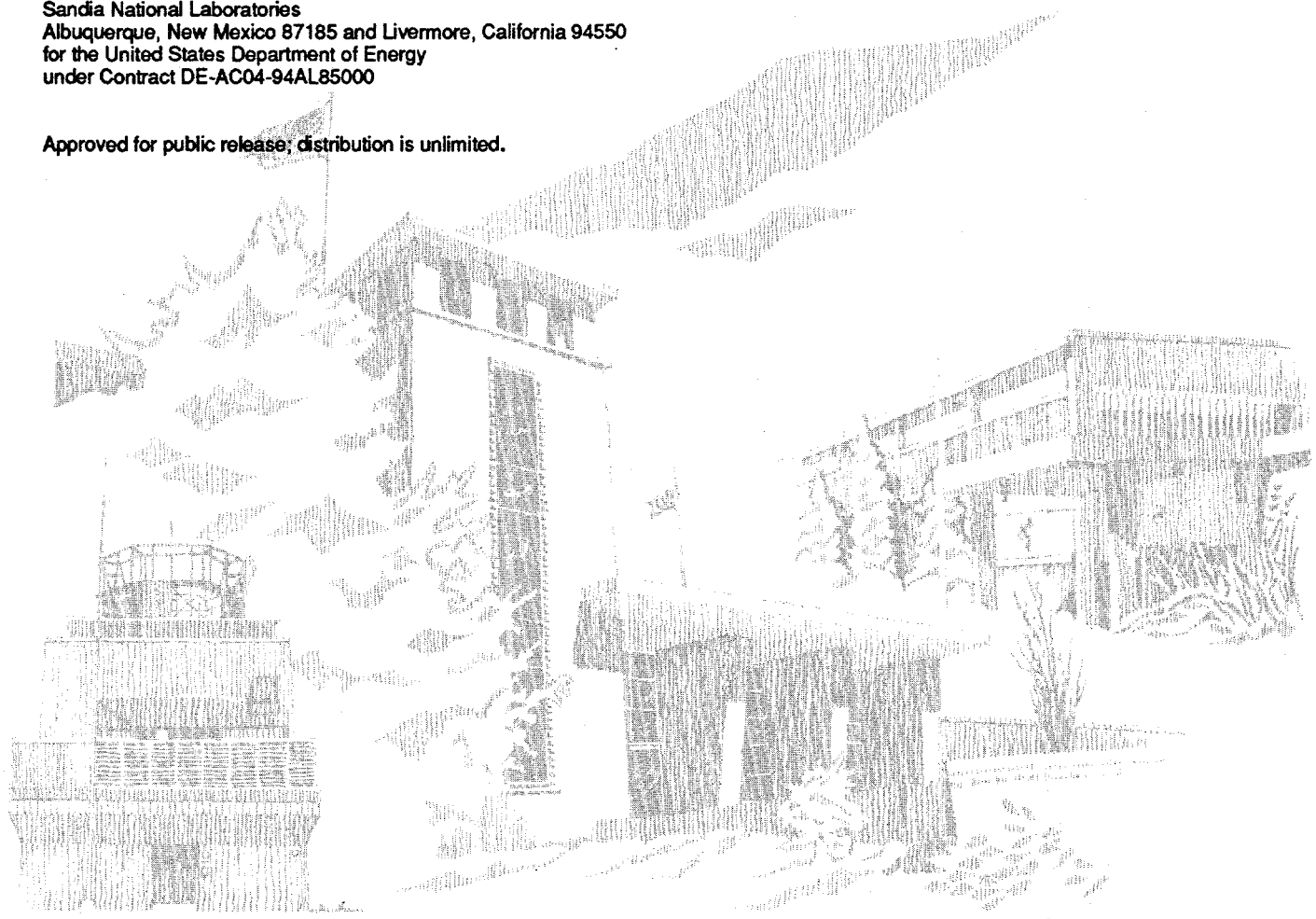

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AQUEOUS FOAM TOXICOLOGY EVALUATION AND HAZARD REVIEW

For the National Institute of Justice
Less-Than-Lethal Force Program

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Abstract

Aqueous foams are aggregates of bubbles mechanically generated by passing air or other gases through a net, screen, or other porous medium that is wetted by an aqueous solution of surface-active foaming agents (surfactants). Aqueous foams are important in modern fire-fighting technology, as well as for military uses for area denial and riot or crowd control. An aqueous foam is currently being developed and evaluated by Sandia National Laboratories (SNL) as a Less-Than-Lethal Weapon for the National Institute of Justice (NIJ). The purpose of this study is to evaluate the toxicity of the aqueous foam developed for the NIJ and to determine whether there are any significant adverse health effects associated with completely immersing individuals without protective equipment in the foam. The toxicity of the aqueous foam formulation developed for NIJ is determined by evaluating the toxicity of the individual components of the foam. The foam is made from a 2-5% solution of Steol CA-330 surfactant in water generated at expansion ratios ranging from 500:1 to 1000:1. Steol CA-330 is a 35% ammonium laureth sulfate in water and is produced by Stepan Chemical Company and containing trace amounts (<0.1%) of 1,4-dioxane. The results of this study indicate that Steol CA-330 is a non-toxic, mildly irritating, surfactant that is used extensively in the cosmetics industry for hair care and bath products. Inhalation or dermal exposure to this material in aqueous foam is not expected to produce significant irritation or systemic toxicity to exposed individuals, even after prolonged exposure. The amount of 1,4-dioxane in the surfactant, and subsequently in the foam, is negligible and therefore, the toxicity associated with dioxane exposure is not significant. In addition, aqueous foams have been used for various applications that include immersing individuals in the foam without protective equipment for various amounts of time. In general, immersion in similar aqueous foams has not resulted in acute, immediately life-threatening effects, or chronic, long-term, non-reversible effects following exposure.

Contents

Nomenclature

ACGIH	American Conference of Governmental Industrial Hygienists
ASTM	American Society for Testing and Materials
BEI	biological exposure indices
CEIL	ceiling, the concentration that should not be exceeded during any part of the working exposure.
COC	Cleveland Open Cup
CNS	central nervous system
HSDB	Hazardous Substances Data Bank
IARC	International Agency for the Research of Cancer
LC50	Lethal concentration - fifty = Concentration that leads to death in 50% of the population studied (used in inhalation studies).
LD50	Lethal dose fifty = Dose that leads to death in 50% of the population studied.
NA	information not available
NCI	National Cancer Institute
NCITR	National Cancer Institute Toxicity Report
NIJ	National Institute of Justice
NIOSH	National Institute of Occupational Safety and Health
NTP	National Toxicology Program
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PM	Pensky-Martens Closed Cup
REL	recommended exposure limit
RTECS	Registry of Toxic Effects of Chemical Substances
SNL	Sandia National Laboratories
STEL	short term exposure limit
TC	toxic concentration
TLV	threshold limit value
TWA	time weighted average (8 hour)

g	grams
hr	hours
kg	kilograms
m^3	cubic meters
min.	minutes
mg	milligrams
ml	millimeters
ppm	parts per million

AQUEOUS FOAM
TOXICOLOGY EVALUATION AND HAZARD REVIEW

For the National Institute of Justice
Less-Than-Lethal Force Program

Introduction

A comprehensive toxicological review was performed on a SNL-developed aqueous foam for the National Institute of Justice Less-Than-Lethal Force Program. Preliminary results indicate that the principal health hazards associated with deployment of aqueous foam include, aspiration/inhalation of the aqueous foam; and skin and eye contact with the foam constituents.

The purpose of the Aqueous Foam Project for the National Institute of Justice (NIJ) is to develop an aqueous foam system to be used in a criminal justice environment and to document any potential toxicological or other adverse health issues associated with criminal justice use of aqueous foam. To this end, SNL is tasked to investigate the health and safety risks associated with completely enveloping humans in foam. This study includes an evaluation of the toxicity of the aqueous foam formulation and its constituents to establish that individuals can be immersed in the aqueous foam for up to one hour with minimal risk of acute, immediately life-threatening effects, or chronic long-term, non-reversible effects. Animal testing or human subject testing with the proposed aqueous foam is not included in this study.

Background

Aqueous foam is an impermanent form of matter in which a gas, often air, is dispersed in an agglomeration of bubbles that are separated from one another by a film of liquid that is 95-98% water. Aqueous foams are generally less than 5% by volume, liquid in air and can be generated in expansion ratios ranging from 20:1 to 1000:1 (air:liquid). The liquid is typically 95-98% water, with the additional 2-5% consisting of surfactants and other additives, such as alcohols and polymers.

Generating high-expansion aqueous foams is an important part of modern fire-fighting technology. Adapting and modifying aqueous foams for certain military and defense applications has also been documented. These applications include the use of foams for obscuration and area-denial purposes, riot and crowd control, and some uses in explosives technology. Civilian uses for aqueous foam include dust suppression and crop treatment.

The proposed use of aqueous foam in the Criminal Justice System for NIJ involves the potential discharge into a populated area as a Less-Than-Lethal Weapon. The discharge of large amounts of medium or high expansion foam into a populated area can inundate personnel resulting in blocked vision, difficulty hearing, spatial disorientation, as well as some discomfort in breathing. The ultimate goal for SNL in the Aqueous Foam Less-Than-Lethal Program for the NIJ was to develop a "no-more-tears" formulation of aqueous foam that could be used in populated prison cells or cell blocks (1). A preliminary study of various surfactants used in high expansion aqueous foams indicated that the ether sulfates containing ethylene oxide were an acceptable surfactant that met the toxicological criteria of non-hazardous. The recommendation to use ether sulfates containing ethylene oxide was made to Pete Rand (1811) in a memo dated April 18, 1995 by the Industrial Hygiene / Toxicology Systems and Process Department (2).

The surfactant chosen for use in the NIJ formulation of Aqueous Foam is Stepan Chemical Company's Steol CA-330, an ammonium laureth sulfate containing three moles of ethylene oxide and less than 0.1% of 1,4-dioxane. It is sold as a 35% aqueous solution. This surfactant was chosen because it meets the toxicological criteria established by NIJ as well as the physical characteristics and foaming capability requirements. For purposes of this study, toxicity and health effects data in the current literature were reviewed for the concentrated aqueous foam formulation and this evaluation is based on the toxicity of the individual components in the surfactant. Adverse health effects due to aspiration and inhalation of aqueous foams by humans are also discussed briefly.

Toxicological Review of Foam Ingredients

AMMONIUM LAURETH (3) SULFATE

Ammonium laureth sulfates (ammonium ether sulfates) are salts of sulfated ethoxylated lauryl alcohol, which conform to the general formula: $CH_3(CH_2)_{10}CH_2\text{-}(OCH_2CH_2)_nOH$ where n is the average number of ethylene oxide moieties. The terminal-OH groups are sulfated and then neutralized with NH_4OH to form the ammonium salt as described (3):

1. Ethoxylation of lauryl alcohol with "n" moles of ethylene oxide,
   $C_{12}H_{25}OH + (CH_2CH_2O)_n \xrightarrow{KOH} C_{12}H_{25}O(CH_2CH_2O)_n H$
2. Sulfation of the product with sulfur trioxide (SO_3) or chlorosulfonic acid ($ClSO_3H$)
   $C_{12}H_{25}O(CH_2CH_2O)_n H \xrightarrow{SO3} C_{12}H_{25}O(CH_2CH_2O)_nSO_3H$
3. Neutralization to form the ammonium salt,
   $C_{12}H_{25}O(CH_2CH_2O)_nSO_3H \xrightarrow{OH\text{-}/NH4+} C_{12}H_{25}O(CH_2CH_2O)_nSO_3NH_4$

The laureth sulfates are clear liquids, soluble in water and alcohol. Used as shampoo, bath, and skin cleansing ingredients, these surfactants also function as emulsifiers, stabilizers, and solubilizers. The concentration of ammonium laureth sulfate in cosmetics ranges from 0.1% to greater than 50%. The aqueous foam developed for the NIJ will use 2-5% of the Steol CA330 to generate a final concentration of ammonium laureth sulfate of 0.7 to 1.8% in water.

Chemical Name(4):

Ammonium Laureth (3) Sulfate
Ammonium Lauryl Ether Sulfate

Molecular Formula (3):

$CH_3(CH_2)_{10}CH_2\text{-}O(CH_2\text{-}CH_2O)_3SO_3NH_4$

CAS Number:

32612-48-9

Chemical and Physical Properties (4):

Approximate MW: 400 g/mol
Melting Point: NA
Boiling Point: NA
Appearance: Pale, clear, yellow liquid
Water solubility: Soluble
Solvent solubility: Insoluble in oils, fats and waxes.
pH: 6.0 - 7.0 @ 10% solution
Specific Gravity: 1.03 g/cc (liquid)

Exposure Limits: No occupational exposure limits for this material have been established by ACGIH, OSHA, or NIOSH (5).

Toxicology: The ether sulfates belong to a class of anionic surfactants with low orders of acute, subacute, and chronic toxicity (3). Exposure to ether sulfates generally results in momentary eye irritation with no permanent eye damage, difficulty in breathing, and some skin irritation following prolonged occupational exposure (6). In subacute (short term) and chronic (long term) feeding tests no adverse effects were observed in the experimental animals with respect to their survival, growth, reproduction, food consumption, hematology, blood chemistry, or urine analysis (7). In these studies, even animals dosed at lethal concentration showed only diarrhea and bloating with no gross or microscopic lesions outside of the gastrointestinal tract.

Ammonium laureth sulfate, likewise, has been shown to produce eye and/or skin irritation in experimental animals and in some human test subjects. The irritant effects are similar to those produced by other ether sulfates, with the severity increasing with concentration (8).

Inhalation Toxicity: The inhalation of ether sulfates results in mild to severe irritation of the mucous membranes of the upper respiratory tract. Animal studies have shown that exposure of the upper respiratory tract to irritants produces a reflex inhibition of respiration which is mediated through stimulation of receptors in the membranes of the respiratory tract. In upper respiratory tract irritancy tests with ammonium laureth sulfates, mice exposed to 1700 mg/m^3 exhibit a 50% reduction in respiratory rate relative to non-exposed mice, with no deaths reported (8). The inhalation LC50 for ammonium laureth sulfate was estimated to be 14250 ppm in the rat (9). This is considered to be practically non-toxic and comparable to the inhalation toxicity of volatile compounds such as isopropanol which have similar LC50s. Comparatively, Ortho-chlorobenzylidine malononitrile (CS), a chemical irritant used in riot control and crowd control, has an LC50 of 5000 ppm.

Dermal Toxicity: Anionic surfactants such as the ether sulfates may irritate the skin by removal of the natural oils producing redness, soreness, and papular dermatitis. Sensitive individuals may experience a thickening of the skin with weeping, cracking, and blistering. Acute dermal effects of ammonium laureth sulfate were tested using clipped, intact and abraded skin of albino rats. Concentrations of ammonium laureth sulfate evaluated in the dermal toxicity tests ranged from 7.5% to 60% and were applied and covered for three days. Reactions were measured at the end of the three day exposure and ranged from slight irritation for the 7.5% exposure to severe irritation at concentrations greater than 60% (3). A dermal LD50 study was performed with a bubble bath formulation containing 22% ammonium laureth sulfate. In this study a 1% solution (0.22% ammonium laureth sulfate) was applied to the backs of the rabbits under rubber dental dam and held in place for 24 hours. The animals were observed for 14 days and then sacrificed and examined for gross pathology. None of the animals died during the observation period, and none showed signs of systemic effects or gross pathological findings at necropsy (3). The acute dermal LD50 was therefore estimated to be 8g/kg body weight (10).

In acute immersion studies performed by this same group, ammonium laureth sulfate produced mild to no irritation in solutions of 0.06% and 0.14% of the surfactant. Furthermore, a 28-day irritation study with unrestrained rabbits on abraded skin was performed with aqueous solutions of ammonium alcohol ethoxy

sulfate. The topical applications contained 50 mg/kg to 200 mg/kg of the surfactant. Histological examinations revealed moderate to severe skin inflammation (3,6).

Ammonium laureth sulfate was also analyzed in a standard Repeated Insult Human Patch test on 189 subjects. A 0.29% solution was used for the induction phase with a 0.15% solutions used as a challenge. During induction, 33% of the subjects had mild to moderate irritation. Adverse effects due to the challenge phase of the experiment were nominal. Therefore, these experiments indicated a minimal potential for irritant contact dermatitis. In further clinical studies, concentrations of the surfactant in the range of 0.1% to 0.3% were essentially non-irritating following initial application. Repeated applications of the sample produced moderate irritation in about 16% of the subjects, with no indication of sensitization following repeat applications. Twenty-one day cumulative sensitivity tests with 0.1% ammonium laureth sulfate showed evidence of a moderate potential for mild cumulative irritation only under continued reapplication and occlusion (3,6).

Eye Toxicity: Prolonged exposure of the eyes to anionic surfactants in the range of 1.3 - 60% can range from non-irritating or transient, mild irritation to severe irritation with the possibility of permanent injury at the high doses (11). The acute ocular irritation of ammonium laureth sulfate was tested according to the Draize method on groups of albino rats. Concentrations of the test solutions ranged from 7.5% to 60% and were instilled into the eyes, with or without wash-out, in doses of 0.1 ml. Effects ranged from transient, mild ocular irritation to severe irritation (3). Clinical studies were performed using 10-20% concentrations of a liquid formulation containing 9% ammonium laureth sulfate (0.9 -1.8% of surfactant). The results of these studies found ammonium laureth sulfate to be non-irritating when instilled into the eyes of 20 human volunteers (12). Additional studies with ammonium laureth sulfate concluded that increasing the degree of ethoxylation of ether sulfates reduces the ocular irritancy and general toxicity of the surfactant (13, 14).

Oral Toxicity: Ingestion of laureth sulfate surfactants generally results in mild toxicity. Ingestion of 1-3 g/kg of these surfactants may irritate the gastrointestinal mucosa and cause abdominal discomfort, diarrhea, intestinal distention, or spontaneous vomiting (15). In acute oral toxicity studies, concentrations of 7.5-27% ammonium laureth sulfate were given to groups of albino rats (3). The results of these studies indicated that the material was moderately to slightly toxic by the oral route. LD50s determined for the surfactant were not very reproducible but ranged from > 0.36 g/kg for test solutions containing 7.5% of the surfactant to >1.21 g/kg for test solutions containing 25% of the surfactant. Acute oral

studies in Sprague-Dawley rats resulted in calculated LD50s of 1.7 g/kg to 3.3 g/kg for solutions of 25% - 26% ammonium laureth sulfate (3). In both the 26% and 27% solutions, all animals that died showed reddened lungs, livers, stomachs, intestines and kidneys at the 3.3 g/kg and 3.9 g/kg dose levels.

Reproductive Toxicity: Tusing et al. evaluated the reproductive effects of ether laureth sulfates in male and female rats. The results of this study indicated that ingestion of 0.1% of ether laureth sulfates had no adverse effect on fertility, litter size, lactation, or survival of offspring. The material induced no changes in blood chemistry or urinalysis in F_1 or F_2 generations, and there were no gross or microscopic abnormalities attributed to the test compound.

The vaginal mucosa of beagles exposed to 0.11% solution of ammonium laureth sulfate five days per week for three weeks showed no gross or microscopic changes. Furthermore a 2.25% concentration of the surfactant caused no irritation when applied to male and female genitalia once a day for two weeks (3).

Carcinogen Studies: Ammonium laureth sulfate is not listed as a carcinogen by IARC, NTP, or ACGIH. Tumorgenicity due to dermal exposure to sodium laureth sulfates was studied in groups of 30 female Swiss Mice. In these studies, 0.1 ml of 5% aqueous solutions applied twice weekly (105 weeks) for a total 1 g exposure did not result in skin tumors and mortality did not differ substantially from controls (3, 6).

Summary: In general, studies have shown ammonium laureth sulfate to have minimal toxicity as a result of acute oral, dermal or inhalation exposure. Exposure to ammonium laureth sulfate at concentrations that are similar to that proposed for the NIJ aqueous foam, results in mild to moderate irritation of the eyes, nose, and mucous membranes. These effects are similar to that produced by other surfactants used in hair-care products. The degree of irritation appears to be related to concentration, duration, and route of exposure. Sensitive individuals may experience an exasperated dermal irritation and thickening of the skin due to the removal of the natural oils in the skin.

Acute exposure to ammonium laureth sulfate has not been shown to produce any permanent injury or to result in systemic toxicity. When compared to other surfactants used in cosmetics, ammonium laureth sulfate is considered to fall in the toxicity range between baby shampoo (nonirritant) and dandruff shampoo (severe irritant) and has been approved for use in the cosmetics industry (3). In addition, increasing the level of ethoxylation of the ammonium lauryl ether sulfate from 1M to 3M has been shown to decrease the irritancy of the product with respect to similar formulations with a lower degree of ethoxylation (13).

1,4-DIOXANE

Dioxane is a colorless combustible liquid with a faint pleasant ethereal odor similar to that of absolute ethanol. Dioxane is produced commercially by dehydrogenation of ethylene glycol. It can also be produced by catalytic dimerization of ethylene oxide in the vapor phase or by reaction of bis(2-chloroethyl) ether or 2-chloroethyl-2'-hydroxyethyl ether with strong aqueous sodium hydroxide (16). It is found in trace amounts (<0.1%) in the Steol -CA330 surfactant.

Chemical Name(17):
1,4-Dioxane

Molecular Formula (18):
$OCH_2CH_2OCH_2CH_2$

CAS Number:
123-91-1

Chemical and Physical Properties (18):
Molecular Weight: 88 g/mol
Freezing Point: 54°F (12°C)
Boiling Point: 214°F (101°C) @750 mmHg
Flash Point: 54°F (12°C) closed cup
Appearance: colorless liquid
Water solubility: Soluble
Solvent solubility: Soluble in alcohol, ether, benzene, acetone, aromatic hydrocarbons, oils, and other organic solvents.
pH: NA
Specific Gravity: 1.04 g/cc (liquid)

Exposure Limits (5, 19):

OSHA PEL:	TWA (skin) - 25 ppm (90 mg/m^3)
NIOSH:	TWA (skin) - 25 ppm (90 mg/m^3)
ACGIH TLV:	CEIL (30 min.) - 1 ppm (3.6 mg/m^3)

Toxicology: 1,4-Dioxane is considered to have a low single dose oral toxicity with an LD50 in the range of 2-8 g/kg in various animal models (16). 1,4-Dioxane is also a suspect cancer hazard with reports of nasal and liver tumors found in rats ingesting high concentrations in drinking water (20, 21). There is, however,

inadequate evidence of its carcinogenic risk to humans, and inhalation studies have failed to exhibit a similar carcinogenic response (22).

Inhalation Toxicity: Experimental studies with humans have shown eye, nose, and throat irritation at concentrations of 200-300 ppm with odor thresholds calculated as low as 3 ppm (19). Inhalation of dioxane caused a variety of signs in guinea pigs, rabbits, cats, rats, and mice, including eye and nose irritation and narcosis. In these studies, concentrations as high as 30,000 ppm were required to produce death in the guinea pig while concentrations of 10,000 ppm for eight hours did not (19). The calculated LC50s for rat and mouse following inhalation exposure were found to be 46 g/m^3 (12,780 ppm) for two hours in the rat and 37 g/m^3 (10,280 ppm) for two hours in the mouse. In general, the guinea pigs were the most sensitive species to dioxane exposure while the mice were the least sensitive.

Subchronic studies performed by Fairley et al. in various animal models found that most animals survived exposures of 2000 ppm for 3 hours/day for up to a total of 100 hours. However, at exposures of 1000 ppm, for the same amount of time, evidence of injury to the liver and kidney were detected (22).

To determine the effects of long-term repetitive inhalation of dioxane, a "lifetime" study was conducted exposing male and female rats to 100 ppm 1,4-dioxane for 7 hr./day, 5 days/week for two years. No evidence of adverse effects of any kind were observed when changes in activity, body weight, or gross or microscopic appearance of organs and tissues of the animals were examined (23, 24).

Dermal Toxicity: Repeated and prolonged contact with 1,4-dioxane liquid can result in absorption of toxic concentrations through the skin. However, epidemiological studies of human exposure indicate that most fatalities due to 1,4-dioxane occur as a result of chronic dermal exposure combined with prolonged or repeated inhalation exposure to the vapor (19, 25).

Experiments in which liquid dioxane was applied to the skin of rabbits, guinea pigs, and mice continuously for 1-5 hours demonstrated that the chemical was rapidly absorbed and produced signs of incoordination, narcosis, and erythema (26). In studies performed by Fairley et al. (22), applications of 1,4-dioxane (5-10 drops for 7-14 weeks) did not exhibit macroscopic abnormalities in the animals studied. In the early weeks of application microscopic renal and hepatic lesions were noted and became progressively worse with repeated application. The effects of dioxane following dermal exposure, become apparent after repeated continuous dosing with the greatest injury occurring after 121 applications.

Eye Toxicity: Levels of 100 - 500 mg in the eyes of rabbits have produced moderate to severe irritation. In humans, studies have shown 1,4-dioxane vapors above 220 ppm cause mild to severe irritation (27, 28).

Oral Toxicity: The acute animal toxicity studies on 1,4-dioxane indicate a low degree of toxicity by the oral route. All the doses studied caused some degree of irritation of the digestive tract, and the target organ appeared to be the kidneys with some effect on the liver. LD50s for the cat, rabbit, guinea pig, mouse and rat were in the slightly toxic to non-toxic range and were reported to be approximately 2, 2.1, 4.0, 5.7, and 6.0 g/kg respectively (16).

Subchronic studies in which dioxane was administered orally to dogs were performed by Schrenk and Yant (29). Dogs given 1,4-dioxane orally over a period of 9 days died with severe liver and kidney damage after a total consumption of 3 g/kg.

Reproductive Toxicity: There have not been many studies on the teratogenic or reproductive effects of 1,4-dioxane following exposure. The results of studies that have been performed have been inconclusive in regard to reproductive or developmental effects of 1,4-dioxane exposure.

Carcinogen Studies: 1,4-Dioxane is listed as an IARC - 2B carcinogen, "possibly carcinogenic to humans, with limited evidence in humans in the absence of sufficient evidence in experimental animals." It is also listed a an NTP-2 carcinogen, "reasonably anticipated to be a carcinogen, with limited evidence from studies in humans or sufficient evidence from studies in experimental animals."

The induction of carcinomas in the nasal cavities and livers of rats fed dioxane at 0.75 to 1.8% in drinking water for 13 months was reported by Hoch and Ligeti (20). These studies examined the toxicity of a daily intake of dioxane greater than 1 g/kg/day. Kociba (21) conducted a similar long-term toxicity study in male and female rats given dioxane in drinking water at concentrations of 0.01 to 1.0% for up to 716 days. In these studies there was a significant increase in hepatocellular carcinomas in rats given 1% dioxane in drinking water and a suggestive increase in the same group in squamous cell carcinomas of the nasal cavities. There were no significant increases in tumors of other types compared to those seen in controls or in rats given lower doses of dioxane.

Three separate epidemiologic studies were done that did not suggest a correlation between increased cancer incidence and dioxane exposure (27).

Summary: Inhalation studies in animals have demonstrated that dioxane exposure can cause narcosis; lung, liver, and kidney damage; irritation of the mucous membranes; and congestion and edema of the lungs. Large doses of 1,4-dioxane administered in drinking water have led to the development of tumors in rats and guinea-pigs. Chronic inhalation studies in animals, however, provided no evidence of increased tumor incidence.

The dioxane contained in the surfactant Steol - CA330 is found in trace amounts and is less that the 0.1% reportable quantity for a carcinogen. Based on the results of the studies discussed above and the information concerning dioxane in the Steol CA-330 surfactant, the levels of 1,4-dioxane found in this product should produce no acute or chronic hazards when handled according to the appropriate MSDS for the surfactant.

Human Exposure to Aqueous Foam

A study to document collected data on past human aspiration exposures due to immersion in aqueous foams was conducted by Tommy Goolsby, Sandia National Laboratories, Department 9611. This study documents first hand knowledge of ten individuals and second-hand knowledge regarding the physiological effects of complete immersion in aqueous foam without protective equipment. The results of this study indicate that immersion in aqueous foam has not resulted in acute, immediately life threatening effects or chronic, long-term, non-reversible effects (30).

Furthermore, an evaluation of an aqueous foam product, Macrofoam, was performed by Rockwood Systems Corporation. Macrofoam is an aqueous foam developed by Rockwood for the control and management of fire, explosion, smoke and dust, as well as the control of hostile intrusion, riots, and crowds. Macrofoam is made of non-toxic ammonium-neutralized sulfate esters (similar to ammonium laureth sulfate), medium chain fatty alcohols, and a phosphate salt. The evaluation performed by Rockwood indicated that Macrofoam will present no known health hazard to a normal individual if washed away within a few hours following exposure. Furthermore, they estimated that for the respiration volume of a 55 kg adult undergoing extreme exercise, an individual would inhale 188 liters of expanded foam per minute. Under these conditions, the time to inhale a toxic dose of Macrofoam was estimated to be 7.5 hours (31).

Aspiration of Aqueous Foam

The aspiration of aqueous foam and the possibility of resulting aspiration or chemical pneumonia is also a concern when evaluating the discharge of aqueous foam into populated areas. Aspiration pneumonia occurs as a result of the abnormal entry of endogenous secretions or exogenous substances into the lower respiratory tract and is generally dependent on two essential features, compromised lower airway defense

mechanisms, and a pathologic event resulting from the aspiration insult (32). Irritating liquids aspirated into the lung may cause a chemical pneumonia. Chemical pneumonitis describes a pulmonary inflammatory reaction to any fluid that is toxic to the lower respiratory tract. Chemical pneumonia, however, is usually the result of the low pH of the aspirate. There is some evidence that suggests that a threshold pH exists in the range of 2 to 3, above which little chemical damage occurs (33).

The pathophysiological changes which occur during fluid aspiration depend upon the composition and volume of fluid aspirated. In studies examining drowning with fluid aspiration, apnea occurred within 10 seconds of fluid aspiration in all animals and persisted from 10 to 40 seconds. Ventricular fibrillation developed in eight out of twenty animals within 5 - 10 minutes. However, the mean quantity of fluid necessary to produce physiological effects of apnea and ventricular fibrillation following aspiration was 17.2 ± 4 ml/kg, 25.5 ± 4.4 ml/kg, and 35.1 ± 5.3 ml/kg body weight in isotonic saline, chlorinated distilled water, and distilled water respectively (34). In another study by this group, it was determined that ventricular fibrillation was common in animals that aspirated 20 ml/kg body weight of liquid but that there were no signs of adverse effects with aspiration of 10 ml/kg (35). In addition, studies to examine the aspiration hazard of various chemicals using a standard aspiration model have determined that for fresh water, a standard aspiration dose of 1.5-2 ml/kg body weight, or 140 mg of water aspirated is required to produce aspiration pneumonia (36, 37).

Animal studies were conducted by Wandall et.al. on the effects of high expansion foams on dogs. The purpose of these studies was to evaluate the effects on blood circulation and blood gases of a living animal breathing in a closed foam filled room and specifically, to examine whether an unconscious individual would have enough oxygen available in his immediate environment to survive a rescue. The results of this study indicated that a person engulfed by foam is exposed to the risk of anoxia if they are unable to move around and release air from the foam. The risk of anoxia however, is apparent only after a 60 minute exposure in the foam for an unconscious individual in a confined space. Another concern examined in this study is the accumulation of carbon dioxide in the breathing zone of an unconscious individual engulfed in foam. The results of this study indicated no abnormal accumulation of carbon dioxide within the 60 minute exposure time. Furthermore, autopsies did not reveal any accumulation of foam or liquid in the trachea or bronchial tree of the animals studied (38).

Conclusions

A space filled with high expansion foam is normally not toxic to persons who may be trapped in the space, since the air entrained in the foam can be quickly released by collapsing the foam. However, depending on the expansion ratio of the foam and the

ability of an individual to move and collapse the foam, some difficulty may be experienced in breathing, and some irritation may occur as the result of dermal or inhalation exposure to the constituents in the foam formulation.

The primary hazard of concern resulting from exposure to aqueous foam is the toxic effects of the constituents of the foam formulation. The aqueous foam developed for the NIJ is a 2-4% solution of the surfactant, Steol-CA330, a 35% ammonium laureth sulfate containing trace amounts of 1,4-dioxane in water. An evaluation of the literature has determined that the Steol-CA330 is non-toxic and is not expected to produce any significant adverse effects following inhalation or dermal exposure to final concentrations of 0.7 to 1.8% as proposed in this study. In addition, the amount of 1,4-dioxane in this aqueous foam formulation is negligible and therefore does not present an increased risk to persons exposed to the foam.

Aspiration of the foam developing into aspiration pneumonia, primarily in an agitated or unconscious individual, is another hazard of concern with deployment of aqueous foam into populated areas. Although pulmonary complications of aspiration seldom occur in healthy animals or adult humans, the status of normal host defense mechanisms such as reflex airway closure during swallowing, cough reflex, mucociliary transport apparatus, and pulmonary cellular defenses is important. Therefore, animals or individuals that are comatose, seizuring, or debilitated or that have swallowing dysfunction or esophageal abnormalities may have a significantly greater potential for developing aspiration pneumonia.

In addition, where products of combustion are introduced into the foam or the quality of the air available for breathing is substandard due to the contaminates present or the temperature of the air, additional exposures to toxic substances may be encountered. It is important, therefore, to ensure that the air used to generate the foam is not contaminated and is breathable quality air. In addition, loss of vision and disorientation in an atmosphere of high expansion foam introduces additional hazards such as tripping and slipping, not discussed in this review.

Overall, the aqueous foam designed for use by the National Institute of Justice for corrections applications is essentially non-toxic. It is made of widely used consumer products that are currently in use in the prison systems in shampoos and bath products. Immersion in this foam for exposure periods of less than one hour should not present a significant hazard to a normal, healthy individual. Special care should be taken however, when immersing an unconscious or highly irritant sensitive individual for periods approaching one hour.

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