CHARACTERISTICS AND GLOBAL POTENTIAL OF THE INSECTICIDAL FUMIGANT, SULFURYL FLUORIDE

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Abstract—Global potential of sulfuryl fluoride (SF), SO_2F_2, the active ingredient in Vikane* Gas Fumigant is being reexamined in light of recent regulatory pressures on competitive fumigants. Researchers in Europe and Japan are investigating the utility of SF as an alternative to Methyl Bromide for control of wood-infesting insects in imported lumber and structures. Presently, SF is the primary structural fumigant in the United States of America for eliminating Drywood termites (Kalotermitidae). Wood-infesting beetles such as Anobiidae and Lyctidae and common household pests such as Carpenter ants (*Camponotus* spp.) and cockroaches (Dictyoptera) also are target pests. SF is not an appropriate alternative for some MB uses such as soil and food commodity fumigations. SF is odorless and colorless, has a high vapor pressure and low boiling point, does not react with household items, is only slightly soluble in water. It rapidly desorbs from materials and aerates from structures. SF is highly toxic to both plants and animals. Insect eggs are less susceptible to SF than are the more active larval and adult stages. SF is not considered to be an ozone depletor or to significantly impact any global environmental processes. Lethal dosages are species specific, and for insects, are temperature dependent. Dosages are calculated using the formula: concentration of fumigant x exposure time. Length of exposure and quantity of fumigant introduced into a structure can be varied by the fumigator to satisfy economic and practical considerations.

INTRODUCTION

The global potential of sulfuryl fluoride (SF), SO_2F_2, the active ingredient in VIKANE Gas Fumigant, is being re-examined in response to recent regulatory pressures on methyl bromide (MB). SF is presently used in these insect fumigation market segments:

1) Above-ground termite control; mainly Drywood termites (Kalotermitidae) but including above ground nests of Formosan subterranean termites, *Coptotermes formosanus Shiraki.*
2) Wood-infesting beetles; (Anobiidae, Cerambycidae, Lyctidae, etc.).
3) Household pests; such as Carpenter ants (*Camponotus* spp.); cockroaches, mainly the German cockroach, *Blattella germanica* (L.),

The major use for SF has been Drywood termite control in the southern coastal regions of the USA due to the fumigant's effectiveness, nonreactive characteristics, and manufacturer support. SF has been widely used in the USA in beetle fumigations of expensive art objects and other valuable materials that can be damaged by MB. Also, SF use for control of Drywood termites is growing in the USA and Caribbean Islands where MB and SF have traditionally competed in the Drywood termite market segments. DowElanco is pursuing SF use only in selected markets in which it provides unique benefits to the fumigator. SF is not an appropriate alternative for some MB uses such as soil and food commodity fumigations.

Stimulated by the present regulatory pressure to reduce MB use in markets where alternative fumigants are available, fumigators are investigating the use of SF to control wood infesting beetles in structures in Europe, and in imported lumber in Japan. MB has been the dominant fumigant in these market segments due to its greater toxicity to beetle eggs.

Fumigation with SF requires a professional attitude and thorough education. DowElanco is enforcing a strict product stewardship policy to augment the training and certification required by government regulatory agencies. SF, like any fumigant, has unique hazards that require full understanding and proper execution of application and safety measures to ensure insect control with minimal hazard to fumigators and the public.

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History of sulfuryl fluoride

In the 1950's, The Dow Chemical Company developed SF to meet the structural fumigator's need for a fumigant that did not cause mercaptan odors, was not flammable, and rapidly aerated from structures. Several early scientific papers describe the research to develop this product and initially define its characteristics and efficacy (Kenaga, 1957, Meikle et al., 1963, Stewart, 1957, Stewart, 1966).

SF was first marketed by The Dow Chemical Company in 1961 in the USA for structural insect control. The Dow Chemical Co. and now DowElanco have been the only marketers of SF.

SF has never been used for soil or stored grain fumigations due to limited efficacy, cost competitiveness of other fumigants, and the potential for residues. DowElanco is not pursuing any registrations for these uses.

Sulfuryl fluoride characteristics

SF is an inorganic chemical composed of 99% SO_2F_2 and 1% inert ingredients (DowElanco, 1992a). SF is inorganic, and is essentially nonreactive with materials generally found in structures. SF is not combustible and has no flash point, but in temperatures exceeding 400°C (752°F) SF will degrade to form hydrogen fluoride (HF) and sulfur dioxide. These chemicals, when combined with water vapor, can form weak acids that can tarnish smooth surfaces such as metal, glass, and ceramics.

SF is odorless and colorless and thus small quantities of chloropicrin are generally introduced into the fumigant atmosphere to warn humans and animals of potential hazard (DowElanco, 1992a). A slight sulfur odor may be detected at high SF concentrations due to inert ingredients.

The vapor density of SF is 3.52, but SF will remain in equilibrium once it is mixed with the ambient air (DowElanco, 1992a). SF has a vapor pressure of 13,442 mm Hg at 25°C (77°F)(MB = 1,610 mm Hg). SF rapidly reaches equilibrium in the fumigant atmosphere and rapidly aerates from structures. SF has a boiling point of −55.2°C (−67°F) at 760 mm Hg, and thus is a gas under all practical fumigation conditions. SF is relatively insoluble in water, 750 ppm at 25°C and 1 ATM (DowElanco, 1992a).

SF is packaged only in steel cylinders 4 feet long and 10 inches in diameter. Each cylinder contains 125 lbs. of SF as a liquid under pressure.

Environment fate

When SF is aerated from a structure it rapidly dissipates into the atmosphere because of its high vapor pressure. SF is broken down mainly through hydrolysis in water to release fluoride and fluorosulfate ions. Ultraviolet radiation and reaction with solid particles in the atmosphere may also catalyze the breakdown of SF (Bailey, 1992).

The relatively small amounts of SF released are calculated to have virtually no impact on the global atmosphere and environment. SF is fully oxidized and thus will not interact with ozone. The relative contribution of SF to acid rain is infinitely small compared to the massive amount of sulfur released into the atmosphere from industry (Bailey, 1992).

Toxicity

Inhalation Toxicity
Inhalation is the critical route of exposure to SF. The acute inhalation hazard of SF is shown below (DowElanco, 1992b).

Acute Inhalation (Rats)

Gender	*Exposure time (hr)*	*LC_{50} (ppm)*
Male	4	1122
Female	4	991
Male	1	3730
Female	1	3021

Time to Incapacitation (Rats)

ppm	*Time (minutes)*
4,000	42
10,000	16
20,000	10
40,000	6

The above exposures produced 100% mortality. All rats were dead or moribund within 3 hrs after the end of the exposure.

For reference, the initial concentration of SF introduced into structures for Drywood termite control is generally 16 mg/l (16 oz/1000 ft^3 or 3850 ppm) or less. Higher initial concentrations are likely when fumigating for control of beetles.

Subchronic inhalation was determined in 13week studies in which rats, exposed 6 hrs/day, five days/week to 30 ppm of SF showed no adverse effects. A concentration of 100 ppm for the same exposure period produced no effects other than mottled teeth (DowElanco, 1992b).

The Permissible Exposure Limit (PEL) for SF is 5 ppm. Positive pressure Self-Contained Breathing Apparatus (SCBA) are required when entering areas where concentrations of SF exceed 5 ppm.

Some symptoms of overexposure are: respiratory irritation, nausea, central nervous system depression, slow or garbled speech, and numbness of extremities. Symptoms may be delayed for several hours. Survival of exposed humans to SF is dependent upon the concentration of SF and the duration of exposure. First aid involves treatment of symptoms and is based on the clinical judgment of the physician. There is no antidote for overexposure to SF.

All people, plants and pets must be removed prior to fumigation. Food, feed and medicinals must be removed from fumigated structures or protected in nylon polymer bags.

Dermal Exposure

Laboratory studies have demonstrated no ill effects in animals through dermal exposure. Sulfuryl fluoride has low lipid solubility and is essentially nonirritating to skin. Liquid SF can cause freeze burns (DowElanco, 1992b).

Reproductive Study

There were no treatmentrelated effects on reproductive or fertility indices, reproductive organs or offspring survival in test animals from a twogeneration exposure to 150 ppm of SF (DowElanco, 1992b).

Teratology Study

There were no teratological effects on rats or rabbits at the highest dose of SF tested of 225 ppm (DowElanco, 1992b).

Genotoxicological Study

The results of the chromosomal aberration, gene mutation, and DNA studies showed no adverse genotoxic effects from exposure to SF (DowElanco, 1992b).

Efficacy

Mode of Action

SF kills insects by disrupting the glycolysis cycle, thereby depriving the insect of necessary metabolic energy (Meikle et al., 1963). Mortality may be delayed for several days, depending on the insect species. Osbrink et al. (1987) reported a range of mean time of mortality for ten termite species from 1.58 days for *Incisitermes snyderi* Hagen, to 3.11 days for *Reticulitermes tibialis* Banks.

Dosage Calculation

The efficacy of SF, like that of all structural fumigants, is affected by four major interdependent factors: 1) initial concentration of fumigant, 2) fumigant loss rate, 3) temperature at the site of insect, and 4) exposure period. The dosage required to kill a pest is measured in OunceHours (mg h/l). OunceHours is defined as the concentration of fumigant multiplied by the exposure time. For insects, the dosage requirement is dependent on the temperature at the location of the pest. As the temperature increases, insect metabolism and respiration increases, which results in a decrease in lethal dosages.

SF offers the flexibility of adjusting fumigant concentration or exposure time to meet time constraints or fumigant cost control objectives. SF fumigations can be as short as 2 hours or, to minimize fumigant costs, may be extended for several days.

To calculate the required dosages for any fumigation situation and pest, DowElanco has developed the Fumiguide* Calculator System. The dosage necessary to kill Drywood termites is used as the standard. Dosages for other pests are calculated using multiplicative factors as listed on the Vikane* label.

The Fumiguide B slide rule is used to determine halfloss times and dosage determination for nonmonitored (halfloss time estimated rather than measured) 20–24 hour fumigations. Tarp condition, seal condition, underseal type (soil type, slab vs. crawl space), volume of structure, and wind speed are inputs necessary to determine halfloss time. The fumigant dosage must also be adjusted to the temperature at the site of the insect.

The Fumiguide Y slide rule is used to determine dosage for fumigations of 2–72 hours and monitored jobs. By measuring the concentration of fumigant at intervals, the precise amount of fumigant necessary can be introduced, thereby minimizing fumigant cost and ensuring successful pest elimination. The Fumiguide electronic calculator incorporates the functions of both slide rules into an easy to use hand held calculator.

Early Efficacy Research

Kenaga (1957) reported on the activity of SF against 14 insects representing the orders Coleoptera, Orthoptera, Lepidoptera, and Diptera. Larval, pupal, and adult life stages of these insects were all killed within a 2–3 fold dosage range. The egg stage, especially for the Coleopterans, required substantially greater dosages to achieve kill. Stewart (1957) determined the lethal dosage of SF for *Incisitermes minor* Hagen.

Termites

In the USA, SF is primarily used to eliminate Drywood termites from structures. Being social insects, only the nonegg life stages of termites must be killed. Osbrink et al. (1987) reported SF lethal dosages for 10 termite species. The 1x dosage calculated using the Fumiguide* system is sufficient for all termites except the Formosan subterranean termite. A 4x dosage is required to ensure a sufficient concentration of fumigant penetrates the moist Formosan subterranean termite nest material. Fumigation trials with 3 termite species (Su and Scheffrahn, 1986) indicated that dry wood does not significantly limit SF penetration and efficacy.

Beetles

Su and Scheffrahn, (1990) tested SF against adults, larvae, and eggs of four museum pests: furniture carpet beetle, *Anthrenus flavipes* LeConte; black carpet beetle, *Attagenus megatoma* (F.); cigarette beetle, *Lasioderma serricorne* (F.); and the hide beetle, *Dermestes maculatus* (DeGeer). Eggs were 7–30 times more tolerant of SF than the larvae and adults, apparently due to reduced permeability of fumigant through the egg shell (Outram, 1967).

Carpet beetle eggs require dosages (Su & Scheffrahn, 1990) which may not be economically practical. The alternative is to fumigate twice at dosages lethal to adults, pupae, and larvae; the second fumigation occurring after all the eggs that survived the first fumigation have hatched. This double fumigation procedure requires detailed knowledge of the insect developmental cycle under the particular environmental conditions at the location of the pest.

Beetle Fumigation Research in Japan

The regulatory pressure on MB has motivated researchers in Japan to initiate development of economical procedures to fumigate with SF to control beetles infesting imported lumber. Their primary pests are: powder-post beetles (Scolytidae), long horned beetles (Cerambycidae), and weevils (Curculionidae).

The present MB fumigation procedure consists of tarping large stacks of lumber on the dock soon after unloading from transport ships. Only one fumigation is conducted, thus a dosage lethal to eggs must be achieved.

Large scale use of SF for lumber fumigation is dependent on improving SF cost efficiencies to compete with MB and alternative control procedures. Potential areas for investigation are:

1) Improved gas confinement
   a) Specially designed fumigation chambers
   b) Reduced permeability tarps
2) Use of Synergists
3) Elevation of ambient temperatures to increase insect metabolism
4) Two fumigations timed to the insect's development cycle.

Cockroaches

Cockroach control with SF is a minor use pattern primarily involving food-handling establishment fumigation to eliminate German cockroaches. Fumigations are generally short-term, ca. 4 hours, to limit out of service time for the business. The lethal dosages for the most tolerant egg stage are equivalent to the Drywood termite dosage (Hardy and Stewart, 1979). Kenaga (1957) reported the LD_{95} for American cockroach *Periplaneta americana* (L.) eggs was 20 times higher than the LD_{95} for adult German or American cockroaches. Lethal dosages for other cockroach species have not been established.

Carpenter ants

Fumigation to control Carpenter ants is mainly conducted in the Northwest region of the USA where these ants are prevalent and housing construction often makes conventional treatment difficult. Fumigation is usually employed after more economical insecticide applications have failed to eliminate the ant infestation. The standard Drywood termite dosage is effective (Rudolf Scheffrahn, unpublished data).

SUMMARY

SF is an effective fumigant for control of a wide range of structural and household insects. Its primary use has been for Drywood termite control in the USA. The practicality of using SF to control beetles in the imported lumber market in Japan is being investigated and it has begun to be used in Germany to control wood-infesting beetles in structures. As MB is phased out of these and other non-agricultural markets, further development of SF fumigation procedures is expected. Future expansion of SF use will be guided by DowElanco's strong product stewardship policy in order to ensure its safe and effective application.

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