Office of Water Programs
California State University Sacramento
Sacramento Area Sewer District (SASD)

RazoRooter II and Sanafoam Vaporooter II:

- Effects on Wastewater Treatment Plant Processes
- Fate and Environmental Impact
- Toxicology and Bioassay Testing
- Public Health Effects to Residents, Bystanders, and Occupational Personnel
- EPA Regulation Updates for Metam Sodium Products

A Literature Review

Prepared For:

Sacramento Area Sewer District (SASD)

Office of Water Programs

California State University Sacramento

March 2010

Abstract:

The herbicidal chemicals RazoRooter (II) and Sanafoam Vaporooter (II) are used in sanitary sewer applications to destroy invasive plant roots that can lead to pipe clogging and SSOs. Razorooter's active herbicidal ingredient is diquat dibromide. The active ingredient in the liquid Vaporooter mix is metam sodium and the solid portion of the mix contains dichlobenil 50W as the active ingredient. Both chemicals are non-selective herbicidal agents that impact non-target plant life. Both are contact, non-systemic herbicides that kill only the portion of a plant contacted by the chemical.

All active ingredients were shown to inhibit wastewater treatment plant (WWTP) processes to various degrees and product testing has revealed that removal during WWTP processes does occur, also to varying degrees. Testing results by the Virginia Polytechnic Institute and the Istanbul Technical University revealed that with plant influent concentrations of 1-10 mg/L, roughly 20% of all introduced diquat dibromide was captured through adsorption to sewage solids and that 80% or more was removed by adsorption in activated sludge systems [1]. Investigators from the same testing concluded that diquat dibromide concentrations up to 12.6 mg/L had no significant negative or inhibitory effects on continuous flow biological wastewater treatment processes [1]. For perspective, application of RazoRooter (II) in a collection system, over an eight-hour workday, would produce less than 1 mg/L diquat dibromide concentration in the influent to a 10.2 mgd wastewater treatment plant.

It is well known that metam sodium inhibits nitrification, but the primary breakdown product of metam sodium, Methyl Isothiocyanate (MITC), is more toxic than metam sodium to nitrifying bacteria at lower concentrations [6]. Testing with MITC concentrations of 2 to 10 mg/L yielded incomplete nitrification, while no effect was noticed below 2 mg/L [6]. Fortunately, sewer environments are contained and reduce the tendency of metam sodium to volatilize or photo degrade to MITC, reducing production of MITC [6]. T. N. Ake, a master's student at Virginia Tech who studied metam sodium inhibition of nitrification found that the threshold for nitrification inhibition was 2 mg/L at 1740 mg/L mixed liquor volatile suspended solids (MLVSS) [6].

Product testing of Razorooter, Vaporooter, and Root X (main ingredient dichlobenil) revealed that these chemicals inhibited and prevented recovery of ammonia oxidation and nitrite oxidation—with RazoRooter being the most potent inhibitor of ammonia oxidation [7]. A no observed effect level (NOEL) for ammonia oxidation of <12.5 mg/L for Razorooter (equivalent to <4.7mg/L diquat dibromide) and 12.5 mg/L of Vaporooter (equivalent to 0.15 mg/L metam sodium) was observed during testing [7]. At Razorooter and Vaporooter concentrations of > 50 mg/L (>18.7 mg/L active ingredient) recovery of ammonia oxidation took more than 4 weeks in batch studies [7]. Vaporooter observed a NOEL for nitrite oxidation of 25 mg/L (0.30 mg/L metam sodium) while Razorooter's observed NOEL was 25 mg/L (9.3 mg/L diquat dibromide) [7]. The recovery times required by BNR processes exposed to high doses of root chemicals can result in violations of effluent discharge limits for nitrogen compounds [7].

The active ingredients of Razorooter and Vaporooter exhibited varying degrees of environmental persistence and toxicity. Diquat dibromide is not a chemical that is persistent in an aquatic environment (disappears in days to weeks) due to its adsorption to sediment, organic plant tissue, and soil [2]. It is, however, extremely persistent in soil, sediments, the organic matter in soil, and clays, but it

bonds with such strength that it is not bio-available and is not a groundwater threat [9, 11]. Diquat dibromide ranges from non-toxic to moderately toxic in fish and invertebrates [9]. Studies conducted on metam sodium in aqueous solutions indicate that it is an unstable compound in surface waters that readily volatilizes to methylamine and MITC [21]. Both metam sodium and MITC are highly toxic to fish and aquatic invertebrates at an LD50 ~53 ppb [21]. Dichlobenil tends to be slightly to moderately persistent in sediments and water, but is extremely persistent in soils [28]. Persistence in soil and water tends to occur in colder climates where volatilization, its primary fate, is inhibited [30, 35]. Dichlobenil bioaccumulates in fish tissue, reduces the reproductive success of fish, and has been found to be acutely toxic to fish [28]. If either RazoRooter or Vaporooter reach natural waterways, mass die-offs of non-target or target plant life may occur, causing eutrophication—which can kill fish.

The severe health and environmental impacts of metam sodium products have led to new EPA regulations. Limits have been placed on areas of application near access manholes and on the equipment used for application. Applicators must now wear an extensive amount of personal protective equipment and this equipment must be made available for support personal and municipal inspectors [21]. A new series of product testing on animals and humans is being required to determine additional toxicity and human levels of exposure. Chemical testing is being required to determine metam sodium byproduct Nitrosodium Methylamine (NDMA) threats and remedies [21]. For safety, signage must be posted during soil fumigant operations [27].

The active ingredients in RazoRooter and Vaporooter can lead to mild to severe bodily harm and death. Diquat dibromide exposure can prove fatal if it is ingested, inhaled, or absorbed through the skin and it is most harmful to the gastrointestinal tract (GIT), kidneys, and liver [9]. In general, irritation of the eyes, nose, throat, dizziness, dermal burns or irritations, ocular burns, conjunctivitis, loss of nails, and nosebleeds are symptoms associated with mild, acute exposure to diquat dibromide [17, 19]. Severe acute exposure can lead to nausea, vomiting, diarrhea, convulsions, tremors, renal failure, GIT damage, ulceration or perforation of mouth/throat/stomach/rectum, and death [19, 11]. The primary acute danger from metam sodium is from its breakdown product MITC—which causes irritative respiratory symptoms, eye irritation, nausea, reactive airways dysfunction syndrome (RADS), exacerbated asthma, and headaches [4, 20]. Chronic exposure to metam sodium can lead to skin rash and severe hepatitis [4, 20]. It is considered a potential vascular oncogen in humans [4]. Dichlobenil can burn or irritate the skin and eyes, cause irritation of the respiratory system, headaches, dizziness, coma, severe chemical-induced acne, loss of the sense of smell, burning or irritation of the skin/eyes, coma, permanent nervous system damage, and can lead to death [28, 33]. It has a high potential to harm human kidneys and the liver and ranks as one of the most toxic chemicals to nasal tissue [28, 33]. Dichlobenil inhibits Taurine transportation to the brain which may lead to Alzheimer's disease [28]. Chronic exposure to the active ingredients in Vaporooter may lead to cancer.

Abbreviations:

SSO—Sanitary Sewer Overflow

WWTP—Wastewater Treatment Plant

BNR—Biological Nutrient Removal

NOD—Nitrogen Oxygen Demand

NOEL—No Observed Effect Level

Kow—Octanol-Water Partition Coefficient

STP—Standard Temperature and Pressure

RADS—Reactive Airways Dysfunction Syndrome

MLVSS—Mixed Liquor Volatile Suspended Solids

NOEL—No Observed Effect Level

GIT—Gastrointestinal Tract

LC_{50}—The concentration needed to kill 50% of test subjects

LD_{50}—The dose needed to kill 50% of test subjects.

RfD—Reference Dose

NDMA—Nitrosodium Methylamine

MITC—Methyl Isothiocyanate

Introduction:

Moisture, warm temperatures, and the nutrient rich flows of sewer lines provide favorable growing spots for tree roots. Roots can fill a pipe to the point of clogging and often require removal. Excessive clogging can lead to SSOs. Several aquatic herbicides, such as Razorooter and Vaporooter, are used as aqueous herbicidal solutions that travel down sewer lines targeting invasive plant life.

RazoRooter

Razorooter is carried by wastewater flow in the form of a foam that contacts root growth in pipes. Razorooter contains 36.4% diquat dibromide and 63.6% inert ingredients [1]. Diquat dibromide is the primary active ingredient in Razorooter and the method of its toxicity to plants is the development of superoxide during photosynthesis which destroys the cytoplasm and cell membrane—ultimately leading to desiccation [2]. Diquat dibromide is a well-known, water-soluble, fast-acting, herbicidal desiccant (kills by drying or removal of water) that kills non-selectively. It will kill only the portions of any immediate plant life it comes in contact with. When used in sewers as Razorooter, it targets roots that have grown into the sewer system. Since its registration in 2000 as a root control herbicide, the root control market has shifted to diquat dibromide because it poses lower risks than the combined use of metam-sodium and dichlobenil [29].

Sanafoam Vaporooter

Sanafoam Vaporooter II contains 30%, by weight, Sodium N-methyldithiocarbamate in the

liquid portion of its mix and also contains 50%, by weight, Dichlobenil 50W in the dry portion of its mix [3]. Sodium N-methyldithiocarbamate (also known as metam sodium) is used as a fumigant pesticide in agriculture and as an invasive root killer in sewers. Metam sodium is a non-selective, contact biocide that kills plant material it contacts. It is non-systemic, meaning it is not taken up into the plant and does not kill the entire plant [38]. Metam sodium will also kill fungi, microbes, and bacteria. It is used in combination with Dichlobenil, which kills plant material by inhibiting metabolic processes unique to plants. Dichlobenil is used in combination with metam sodium primarily because of its root regrowth inhibition properties.

Adverse developmental, oncogenic, and genotoxic effects in tested animals have led to many human risk assessments for metam sodium and its byproducts—primarily the highly toxic gas Methyl Isothiocyanate (MITC) [4]. Additional dangers to humans, livestock, crops, and the environment, resulted in metam sodium's 1994 designation as a "restricted use" pesticide and its label as a Toxic Air Contaminant in 2003 [4]. Its byproduct, MITC, was also listed as a Toxic Air Contaminant in 2003[4]. In 1998, metam sodium was a part of California Proposition 65 and listed as an agent known to cause reproductive/developmental toxicity and cancer [4]. Metam Sodium released in waters exposed to the open atmosphere and sunlight always produces MITC. In enclosed sewers, metam sodium has a much lower tendency to form MITC. In sewers, the USEPA has classified all metam sodium products as restricted use during the 2008 re-registration eligibility decision (RED) [5].

Herbicides, such as Razorooter and Vaporooter are injected into sewer lines to control root growth in sewer systems, which results in an eventual mixing of their active ingredients with raw sewage, settled sewage, and activated sludge at a wastewater treatment plant. These chemicals can pose danger to humans, animals, and the environment in large concentrations and have some inhibitory effects on WWTPs [4, 7, 21].

Effects on Wastewater Treatment Plant Operations

Diquat Dibromide

A study by the Virginia Polytechnic Institute and the Istanbul Technical University to test the effects of diquat dibromide was conducted on both fully aerobic and biological nutrient removal (BNR) activated sludge systems. The systems were tested in a continuous flow form by diverting raw sewage from the main sewer that serves Blacksburg, Virginia. A BNR system was used as a control system while one separate fully aerobic and one biological nutrient removal (BNR) activated sludge system was used for testing. Both systems were fed by municipal sewage with added diquat dibromide in concentrations that ranged from 0.93 to 12.6 mg/L. The sorption rates of the chemical by raw sewage and activated sludge solids were initially determined through batch testing. In all test trials in both systems, the diquat dibromide had no observable negative impacts on any of the two tested continuous flow systems [1]. Experimental monitoring revealed that only a small portion of diquat dibromide particles adsorb to raw sewage [1]. However, due to the massive amount of biomass solids present, most of the diquat dibromide was removed during the activated sludge treatment process [1]. Specifically, when the diquat dibromide concentration was 1 mg/L or less, 94% or more of the chemical was removed by the activated sludge process [1]. In concentrations of 1-10 mg/L, testing results revealed that roughly 20% of all introduced diquat dibromide was captured through adsorption to sewage solids and that 80% or more was removed

by adsorption in the activated sludge process [1]. It was observed that slightly acidic pH conditions can result in the release of adsorbed diquat dibromide particles back into solution [1]. Activated sludge MLSS concentrations of 876 to 3,808 mg/L were used to adsorb diquat dibromide from a 10 mg/L diquat dibromide solution. The total diquat dibromide sorption per activated sludge particle varied from 0.00157 to 0.00458 mg/L, with the higher concentration occurring at the lower MLSS concentration [1]. However, the highest MLSS concentration removed the most diquat dibromide (73% removal) over the lowest MLSS concentration (40% removal) [1]. Results from continuous flow and batch tests indicate that diquat dibromide concentrations have no detrimental impact on biological wastewater treatment processes when the concentration is kept at or below 1 mg/L and little significant inhibitory impact with diquat dibromide concentrations up to 12.6 mg/L [1]. It is important to note that 1 mg/L of diquat dibromide is a larger dose than a 38,700 m3/day (10.2 mgd) plant without primary sedimentation would receive in an 8 hour work day of chemical application in the collection system [1]. Overall, there was little observed effect on denitrification in the BNR system. In the fully aerobic experimental system, decreasing nitrate concentrations confirmed that diquat dibromide actually stimulates denitrification [1]. Batch reactor tests on nitrifier bacteria using sludge from the last aerobic reactor of the continuous flow system indicate that diquat dibromide concentrations of up of 1 mg/L had little effect on nitrifier growth rate [1]. A 10 mg/L concentration inhibited growth rates by about 6% against the control sample but because the growth rates observed were higher than typical rates, testing still indicates that the 10 mg/L sample was hearty and strong [1]. In high concentrations (above 10 mg/L), diquat dibromide led to significantly higher oxygen uptake rates in activated sludge [1]. The discharge concentration diquat dibromide was significantly smaller than the influent concentration. For influent concentrations of 10 to 12.6 mg/L, effluent concentrations of up to 1.63 mg/L were observed [1].

Effluent samples were tested for chronic and acute toxicity on *Ceriodaphnia Dubia* (water fleas). Toxicity testing revealed that effluents were clearly non-toxic with diquat dibromide influent concentrations up to 1 mg/L [1]. Only mild to slight toxicity was observed with influent concentrations up to 12.6 mg/L [1]. It was observed that fewer dissolved solids yielded slightly greater toxicities [1].

Metam Sodium/MITC

T. N. Ake, a master's student at Virginia Tech, determined that MITC is more toxic than metam sodium to nitrifying bacteria at lower concentrations; however, because metam sodium is stable in sewers (photolysis is prevented in sewers), breakdown of metam sodium in sewers does not produce enough MITC to pose a problem to nitrifying bacteria [6]. The exact concentration of metam sodium and/or MITC that inhibits nitrification was difficult to identify in Ake's studies due to fluctuations in environmental, treatment plant, and application conditions. Based on his findings, Ake concluded that metam sodium is the primary contributor to the inhibition of nitrification at WWTPs [6]. For WWTP operators, Ake recommends a target concentration of 2 mg/L metam sodium in activated sludge at a MLVSS concentration of 2000 mg/L [6]. The threshold for nitrification inhibition was determined by Ake to be 2 mg/L at 1740 mg/L MLVSS [6]. Testing with MITC concentrations of 2 to 10 mg/L yielded incomplete nitrification, while no effect was evident below 2 mg/L [6]. The US EPA has identified situations that are known to cause inhibition of nitration in WWTPs: 1.) upstream application of metam sodium in close-proximity to the WWTP; 2.) applications of metam sodium in sewers with low volume; and 3.) excessive upstream applications of metam sodium [6].

Razorooter/Vaporooter Testing on WWT Processes.

Batch studies performed at Stanford University on fresh activated sludge showed that Razorooter and Vaporooter inhibited and prevented recovery of ammonia oxidation—with Razorooter being the most potent nitrification inhibitor between Razorooter, Vaporooter, and Root X [7]. A NOEL for ammonia oxidation of <12.5 mg/L for Razorooter (equivalent to < 4.7mg/L diquat dibromide) and 12.5 mg/L of Vaporooter (equivalent to 0.15 mg/L metam sodium) was observed during testing [7]. A side study on Root X (active ingredient dichlobenil) showed a NOEL for Dichlobenil of 2.75 mg/L [7]. At Razorooter and Vaporooter concentrations of > 50 mg/L (>18.7 mg/L and > 0.6 mg/L active ingredients, respectively) recovery of ammonia oxidation took more than 4 weeks in batch studies [7]. No observed recovery was made for Vaporooter concentrations in excess of 1 g/L (>12 mg/L metam sodium) [7]. A subsequent testing on Sanofoam Vaporooter was required by The Hampton Roads Sanitation District in Virginia prior to the allowed use of the chemical. The testing results indicated that the threshold for observed nitrification inhibition effects was 25 ppm (or 25 mg/L), a relatively similar concentration to that identified in other studies [8]. In addition to ammonia oxidation inhibition, both chemicals inhibited nitrite oxidation [7]. Vaporooter observed a NOEL for nitrite oxidation 25 mg/L (0.30 mg/L metam sodium) while Razorooter's observed NOEL was 25 mg/L (9.3 mg/L diquat dibromide) [7]. Minimal nitrite oxidation was observed at 5.5 mg/L Dichlobenil and no recovery of nitrite oxidation was observed at > 1 g/L Vaporooter [7].

Diquat Dibromide—Fate and Environmental Impact

Diquat dibromide is not a chemical that is persistent in an aquatic environment. Its low persistence in water makes it a preferred choice for use as an agricultural herbicide where swimmers, livestock, residents, and occupational personnel may come in contact with the water [16]. Its fate is short-lived in an aquatic environment due to its adsorption to particles and sediment as well as its long retention in plant tissues [2]. Water column concentrations decline below levels of detection within days to weeks due to adsorption to soil, sediment, terrestrial and aquatic plant life, and organic matter [2]. Particles responsible for turbidity act as an effective natural tool for diquat removal from water [14]. In neutral pH waters, the half-life for photo degradation of diquat is 74 days [17]. Based on all forms of removal, forty-eight hours is a typical water column half-life for the presence of diquat dibromide in surface waters [9].

Substances with greater hydrophobic behavior tend to bio-accumulate in fish tissues [37]. The Octanol-Water Partition Coefficient (Kow) is a measure of hydrophobic behavior [37]. The low Kow value (0.000025) of diquat suggests a low bioaccumulation potential [2, 12]. Diquat dibromide has a greater toxicity to fish in soft waters at a low pH and is known to have chronic effects on invertebrates (Hyallela azteca) [2].

Diquat dibromide is extremely persistent in soil, sediments, the organic matter in soil, and clays. Half-lives of the chemical in soils in excess of 1000 days have been reported [9]. A study conducted on diquat in pond water revealed that applied diquat dibromide disappeared within days of application, but persisted in sediments beyond 160 days [11]. Diquat dibromide binds to sediments and soil due its double positively charged diquat cation and once bound it is no longer bio-available [11]. Its strong adsorptive properties towards soils suggest that it will not infiltrate through soil into groundwater, be taken up by microbes and plants, or be broken down by photochemical degradation with ease [9].

Erosion studies on diquat treated soils conclude that diquat dibromide bonds quickly and strongly to soils and remains biologically inactive in all forms of surface waters [9]. Once bonded, there has been no evidence of extensive desorption of diquat dibromide back into the environment [15]. Ingestion cannot break the bond of adsorbed diquat dibromide—thus adsorbed diquat cannot be metabolized [12]. A US soil accumulation study revealed that 16% of applied diquat remained in soil 11 years after annual application at a rate of 1 kg diquat/ha/yr and soil residue studies have determined a maximum residue in soil of about 0.11 mg/kg [15]. According to the World Health Organization (WHO), the rate of degradation in soil, while slow, was not too slow to allow for infinite diquat residues to build up in soils and sediments [13]. In case of spills, the tight binding nature of diquat makes clays very useful in accident containment [14].

While some laboratories have been successful in tests, diquat dibromide resists aerobic and anaerobic microbial degradation [9]. However, because it adsorbs to soil so rapidly in natural conditions, biodegradation does not play a significant role in its fate [11]. Diquat Dibromide has been found to have an aerobic biodegradation half-life of 31-50 days and an anaerobic biodegradation half-life of >270 days [12].

Diquat dibromide rapidly kills plant life to which it makes contact by inhibiting cell respiration through the release of strong oxidizers that inactivate cells and cell functions [9]. Diquat dibromide is a potent aquatic weed controller in extremely low concentrations [9, 11]. The rapid killing ability of diquat dibromide usually destroys any translocation mechanisms in the plant at the area of contact—essentially limiting diquat's killing ability to only the areas of plant life to which it makes contact [9]. If large amounts of diquat dibromide enter an aquatic habitat with dense plant life, the resulting plant die-off could result in eutrophication which can kill fish. To prevent such impacts, manufacturers specify that water concentrations of diquat dibromide should not exceed 2 mg/L [10].

Due to its nature as a non-selective aquatic herbicide, substantial risk to non-target plant life and aquatic life exists if spills, SSOs, WWTP releases of untreated or partially treated sewage, or other forms of accidental or intended discharges occur. However, when herbicidal doses are applied correctly and in the advised amounts for aquatic herbicidal use, diquat dibromide concentrations decrease to undetectable levels within 7-14 days—limiting damage potential [10].

Diquat dibromide ranges from non-toxic to moderately toxic in fish and invertebrates [9]. At the application rates advised by most manufacturers, diquat dibromide is not harmful to most fish [10]. Eight-hour concentrations of diquat dibromide yielded LC50 values for Rainbow Trout at 12.3 mg/L and Chinook Salmon at 28.5 mg/L. Ninety-six hour testing yielded LC50 values of 16 mg/L, 20.4 mg/L, 245 mg/L, 60 mg/L and 170 mg/L for Northern Pike, Fingerling Trout, Bluegill, Yellow Perch, and Black Bullhead [9]. The toxicity of diquat dibromide varies with fish size and water hardness [10]. In general, acute exposure LC50 values fluctuated from 12-90 mg/L for 24 hour exposures, 6-44 mg/L for 48 hour exposures, and 4-36 mg/L for 96 hr exposures [10]. The main risk for fish results from decreased oxygen levels following the decay of weeds killed by diquat used as an herbicide. Respiratory stress in Yellow Perch has been observed at levels expected during herbicidal treatment [12]. It is confirmed to be slightly to highly toxic on invertebrates and estuarine species [10].

The potential for significant atmospheric concentrations of diquat dibromide is limited by the low volatility of diquat [11]. The photolysis half-life of diquat dibromide in air is two days [14].

The EPA's regulatory conclusion on properly labeled and used diquat dibromide products is that the chemical "will not pose unreasonable risks or adverse affects to humans or the environment" [9].

Diquat Dibromide—Toxicology and Bioassay Testing

Acute Toxicity

Diquat dibromide is considered moderately toxic through ingestion and dermal contact [9]. In animal studies, ingestion led to mild to severe mouth, throat, esophagus, and stomach irritation. Additionally, following the ingestion of large doses of diquat dibromide, nausea, severe dehydration, kidney failure, alterations in body fluid balances, vomiting, gastrointestinal discomfort, chest pain, kidney failure, toxic liver damage, and diarrhea were observed. Testing has yielded Oral LD50 values of 120-235 mg/kg in rats, 233 mg/kg in mice, 188 mg/kg in rabbits, and 187 mg/kg in guinea pigs and dogs, and 30-56 mg/kg in cows [9, 17]. Moderate acute dermal toxicity was indicated from rabbit studies that observed skin reddening, skin thickening, skin inflammation, skin scabbing, ulceration of gastric mucosa, degeneration of tubules in kidneys, and congestion of lungs and blood vessels [9]. Rabbit dermal LD50 values of 400-500 mg/kg were observed with symptoms similar to severe ingestion [9, 17]. Rare dermal necrosis was observed in animal studies [17]. Absorbed diquat tends to accumulate in the kidneys and was detectable in other tissues in lower amounts, but within a week of return to animal control diets, it was not detectable in any tissue [10]. Large doses taken dermally or ingested may lead to convulsions and tremors [9]. Moderate to severe eye irritation has been observed in rabbits [9]. In rats given oral doses, gastrointestinal tract absorption was minimal and excretion through urine and feces occurred within 48 hours of ingestion at 4-11% and 84-97% respectively [10]. Acute inhalation of diquat dibromide may lead to moderate to severe oral and nasal irritation, headaches, forms of respiratory distress, increased lung weight, and symptoms similar to ingestion—with similar results observed in dogs [9, 10]. Diquat dibromide was found to have a half-life in blood (rats) of approximately 4 hours [15].

Chronic Toxicity

Chronic toxicity tests in dogs and rats yielded increased incidence of cataracts and decreased vision at increased dose levels—with cataracts being the most sensitive symptom to chronic diquat dibromide exposure [9, 10]. The 1 year oral NOEL for cataracts in rats was 0.66 mg/kg/day and was 0.5 mg/kg/day for dogs [17]. Two year extended feeding tests on rats at levels of 2.5 to 4 mg/kg/day yielded no negative effects other than reduced weight gain and growth [9]. Prolonged dermal exposure is thought to cause inflammation of the skin and kidney complications [9]. Evidence from animal testing demonstrates that diquat dibromide causes toxicological damage in the gastrointestinal tract, eyes, kidneys, liver, lungs, inflammatory lesions of large intestine, shrunken adrenal glands, and reduced kidney weights [9, 17]. Extended length feeding studies on rats at 15 and 36 mg/kg/day produced limited tumors and, based on these tests, the investigators concluded that diquat dibromide is not carcinogenic [9, 10]. The EPA's Reference Dose/Peer Review Committee classified diquat dibromide as a Group E carcinogen in 1994 because the lack of evidence produced through the carcinogen testing on two species (rats/mice) pointed to diquat dibromide being non-carcinogenic in humans [10]. Inhalation studies performed on rats resulted in increases in body weight, lung lesions, mottling, and reddening of female lungs, but all effects were reversible—except for reddening of the lungs [10].

Developmental and Reproductive Toxicity

Diquat Dibromide is a Bipyridylium herbicide. Embryotic and teratogenic effects are produced in avian, amphibian, mammalian, and dipteran organisms with exposure to Bipyridylium herbicides [18]. The Department of Biology at Frostburg State University conducted a study on mallard eggs to explore the degree of such effects. Eggs submerged in diquat solutions exhibited physical defects in brain, eye, bill, limb, skeletal formation as well as increased lipid peroxidation [18]. An LC50 of 19.5 g/L was determined for eggs and 9.6 g/L for hatchlings [18]. Only eggs exposed to diquat exhibited deformities while hatchlings experienced no physical deformities due to the later stage of exposure [18]. The study concluded that diquat would have little effect on the development of mallard embryos in the concentrations expected to be produced through weed/root control in the natural or sewer environment, however, larger concentrations reaching surface lands could greatly affect the development of avian species [18]. The toxicity of diquat is thought to develop from lipid peroxidation and the destruction of antioxidant mechanisms for defense [18]. Subsequent studies have confirmed that toxicity is primarily the result of oxidative stress [18]. Glutathione is an important antioxidant defense that repairs damaged DNA and diquat inhibits such antioxidants and alters the form and function of proteins and enzymes—leading to lipid peroxidation [18].

In male and female rats, diquat dibromide reduced food consumption and growth, but fertility and mating frequency were unaffected, except for slight decreases in the number of pups [9, 10]. An oral NOEL for weight gain in rats was established at 4 mg/kg [17]. Further rat/mice studies at higher dose levels revealed decreased fetal weight, the complete non-development of certain bones, skeletal disfigurations, kidney effects, and kidney hemorrhages in rat fetuses [10, 17]. The NOEL for skeletal defects was observed at 12 mg/kg in rats and 0.33 mg/kg in rabbits [17]. At 25 mg/kg/day only slight growth retardation was observed and overall evidence suggests that it is unlikely that diquat dibromide will cause reproductive effects in humans under normal circumstances [9].

Teratogenic and Mutagenic Toxicity

During pregnancy, rats were given injected doses (14 mg/kg/day) of diquat dibromide while pup development and birthing was monitored [9]. Skeletal defects and skipped bone development were observed in the rat pups from the diquat treated mothers [9]. At 0.5 mg/kg/day injected intraperitoneally, no birth defects, mutations, or skeletal formation of any kind were observed in rats [9]. Feeding at 10 mg/kg/day in rats and mice yielded no mutagenic aberrations [9]. Similar mutagenic tests, performed on human lymphocytes, produced chromosomal aberrations [17]. Animal testing yielded primarily negative results for mutation or chromosomal aberrations. Mutagenic studies suggest that diquat dibromide cannot alter the genome of developed animals, but induces chromosomal effects on developing offspring [17]. Testing indicates the unlikelihood of diquat dibromide producing teratogenic effects in humans at expected exposure levels [9].

Diquat Dibromide—Health Effects to Residents, Bystanders, and Occupational Personnel

Human exposures to diquat dibromide have yielded a wide range of acute and chronic health symptoms. Diquat dibromide is classified as a substance of moderate toxicity for eye exposure and has been placed in toxicity category II for these effects [9]. It is slightly toxic at acute levels of exposure for oral and inhalation routes—for which these effects have placed it in toxicity category

III [9]. The EPA has concluded that diquat dibromide is toxic via repeated dermal exposure, but it is not a skin sensitizer [9]. Dermal toxicology assessments on rabbits and rats have placed it in toxicity category IV for dermal effects [9].

Diquat dibromide exposure can prove fatal if it is ingested, inhaled, or absorbed through the skin. Workers faced with dermal exposures to concentrated diquat dibromide solutions have experienced fingernail softening and changes in color of the nail—with some instances of nails not growing back [9]. A study of dermal diquat dibromide exposure on the forearms of six male volunteers resulted in 0.3% of all applied doses being recovered in urine and 1.4% absorbed through the skin [17]. Testing was performed with constant contact for 24 hours and was used to simulate the work conditions of chemicals getting into clothing [17]. The longest reported disability from diquat poisoning was 74 days in length and resulted from repeated and prolonged dermal exposure that required treatment by skin grafting [17]. Accounts of accidental splash exposure to diquat dibromide have led to severe acute ocular injury starting with mild irritation that led to burns and scarring of the cornea [9]. Acute dermal, inhalation, intravenous, and oral exposures to diquat dibromide resulted in 90% excretion of the dose within the first day and the rest of the dose within the next day—primarily in the urine [9]. Human studies also show that diquat has a half life in blood of about 4 hours and roughly 62% is excreted in urine within a 5 day period [17].

Between 1982 and 1990, 51 illness reports and one suicide were recorded in association with exposure to diquat in the US [17]. There have been additional suicidal records since that time frame and even accounts of homicidal diquat poisoning in Japan [14]. Hand held applicators are responsible for 60% of all illness/injury cases [17]. Based on studies of such deaths and illnesses, the estimated human LD50 of diquat is 100 mg/kg—though deaths have been noted to occur at doses of 67 mg/kg [14]. Lethal ingestion in humans and diquat-feeding studies on monkeys indicate conclusively that diquat is most harmful to the gastrointestinal tract (GIT), kidneys, and liver [9]. Human ingestion has led to irritation of the mouth, throat, and stomach in small doses and severe ulceration/perforation of the stomach, throat, and bowel in large doses [9, 11]. Six of ten cases of ingestion resulted in death and the lethal dose involved ingestion of approximately 15 ml diquat dibromide followed by toxic responses of the gastrointestinal tract, kidneys, and brain [11]. In the cases of human survival, ingestion was less than 5 ml—but renal and gastrointestinal damage resulted [11]. When ingested in large doses, death occurs in the glandular tubes that process urine in the kidney [9, 16]. It is important to note that all these doses are significantly higher than amounts people swimming in correctly treated waters would absorb or ingest [11].

Diquat dibromide causes drastic alterations to the distribution of bodily water by concentrating it in the stomach—causing dehydration elsewhere in the body and ulceration of the stomach leading to the vomiting of blood [11]. Analysis of human deaths has demonstrated that dehydration tends to play a key role in death by ingestion [11]. The EPA has established an oral reference dose (RfD) of 0.0022 mg/kg/day based on a multi-year rat study performed by the Chevron Chemical Company [11].

In general, irritation of the eyes, nose, throat, dizziness, dermal burns or irritations, ocular burns, conjunctivitis, loss of nails, and nosebleeds are mild acute human symptoms of diquat dibromide exposure [17, 19]. As noted earlier, severe acute exposure can lead to nausea, vomiting, diarrhea, convulsions, tremors, renal failure, gastro intestinal tract damage, ulceration/perforation (mouth, throat, stomach, rectum), and death [19, 11].

Incidental diquat dibromide ingestion by a 2.5 year old boy resulted in death 143 hours (6 days) later [14]. His death was characterized by progressive neurological dysfunction brought about by brain stem lesions. Observations on the effect of such lesions have suggested that Parkinson's disease-like effects are possible with exposure to diquat dibromide [14]. Based on animal toxicology, cataracts are of concern, but there have been no epidemiological reports of cataracts in humans from repeated occupational or environmental exposures [14].

Metam Sodium/MITC—Fate and Environmental Impact

A massive metam sodium spill from a derailed tank car occurred on July 14, 1991 at Cantara Loop in the Siskiyou Mountains of Northern California [20]. The derailed car fell into the canyon formed by the Sacramento River and a resulting puncture released 19,000 gallons of a 32.7% (by weight) metam sodium pesticide [4, 20]. The toxic plume traveled 40 miles down river over three days, killed virtually all aquatic life, and resulted in the formation of the break-down product methyl isothiocyanate (MITC)—a potent airborne irritant [20]. The Cantara Loop Spill is one of the largest environmental and medical disasters in California history. Over 700 residents were seen and evaluated for medical complications in the days following the spill [20]

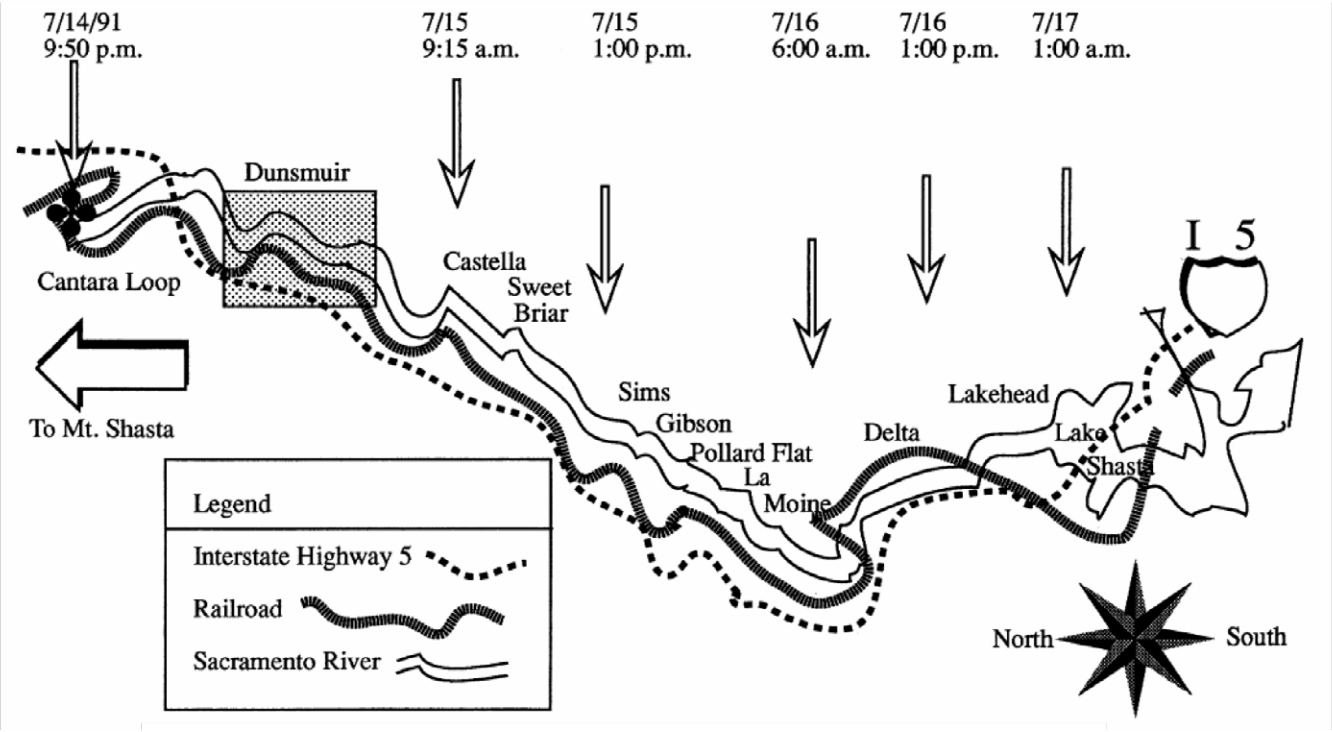

Figure 1. Migration of the leading edge of the metam sodium plume down the Sacramento river

Image from: Chest, Official Publication of the American College of Chest Physicians. 1994. P. 501

Environmental Breakdown Products

The spill at Cantara Loop was a major wake-up call to the potential disasters posed from intentional or unintentional release of massive quantities of toxic herbicides into the aquatic environment. When released into the environment, Metam Sodium products break down into multitudes of hazardous

byproducts. Methyl Isothiocyanate (MITC) is the primary breakdown product to be discussed in detail alongside metam sodium. Other important byproducts of mention are: Methyl Isocyanate (MIC), Hydrogen Sulfide, Carbon Disulfide, Methylamine, Carbonyl Sulfide.

MIC, a clastogenic and cytotoxic compound, was responsible for up to 5000 human deaths in the 1984 factory incident in Bhopal India [4]. MIC is a severe pulmonary irritant and evidence of pulmonary sensitization was found in human victims at the Bhopal incident [4]. In humans, MIC has several noted effects besides pulmonary complications. Photophobia, corneal ulcerations, ocular pain, diminished vision, cataracts, excessive menstrual discharges, night blindness, and increased fetal loss have been reported [4]. The tested LC50 for most animals is 6-12 ppb and a study of MIC concentration in air after agricultural use in Kern County showed 0.09 to 2.5 ppb present [4]. MIC is clearly a byproduct of concern.

Hydrogen sulfide is formed through the same processes as MIC and it acts as a cyanide compound by inhibiting and stopping intracellular electron transport [4]. Human exposure has led to respiratory irritation and pulmonary complications [4]. Pulmonary obstructions are major findings in humans [4].

Carbon disulfide is a particularly hazardous byproduct of metam sodium. In 30 minute inhalation exposures, it is life threatening to humans at 3210-3850 ppm and lethal at 4815 ppm [4]. Oral exposure of 15 ml is fatal [4]. Dermal and ocular exposure has led to recorded instances of severe burns [4]. Chronic inhalation exposure to concentrations of 3-320 ppm can lead to nervous system degeneration, cardiovascular complications, and kidney disorders—with repeat, long-term exposures [4].

Methylamine and Carbonyl Sulfide are the last major breakdown products of note. Both are produced by cleavage of metam sodium under acidic or metabolic conditions [4]. Methylamine is an irritant to the eyes, nose, and throat and can lead to pulmonary edema [4]. Acute inhalation of Carbonyl Sulfide at above 1000 ppm can result in instant fatality without warning. Symptoms of Carbonyl Sulfide poisoning following sub-lethal inhalation include giddiness, confusion, unconsciousness, vomiting, and cardiac arrhythmia [4].

Metam Sodium products produce Nitrosodium Methylamine (NDMA)—a likely human carcinogen [36]. On June 11th, 2001, the Orange County Sanitation District conducted NDMA sampling in sewers following applications of Sanofoam Vaporooter II. Sampling took place in a residential sewer in Tustin. Prior to application, Sanofoam Vaporooter was found to have 1 ppm NDMA in a 100 lb sampling—the highest reading from a single point source [36]. Downstream monitoring observed NDMA concentrations as high as 0.49 mg/L in the same sewer line [36]. Additional monitoring before and after a Vaporooter treatment in a sewer trunk line in Rancho Cordova, California, yielded sufficient evidence of NDMA being a byproduct of metam sodium application—as concentrations of up to 2000 ng/L NDMA were observed during treatment [36].

Based on the above, NDMA has been located in sewage influents to WWTPs and Sedlack, et al. reported that metam sodium-containing root control chemicals and DTC-containing metal treatment systems accounted for approximately 50% of identified single point sources of NDMA based on field observations [36]. Samples from wastewater treatment plants and industrial sources yield an average NDMA concentration of 80 ng/L with maximum occurrences of 790 ng/L [36]. Monitoring NDMA removal during secondary wastewater treatment yielded variable results of 0-75% removal—it is unknown at this time what has led to the variability [36]. Disinfection with

chloramines has been observed to increase NDMA concentrations when chloramines react with dimethylamine and various nitrogen compounds [36].

Once inside WWTP influents, NDMA is extremely difficult and costly to remove. Plants in California have faced extreme difficulties meeting NDMA drinking water DHS action levels of 10 ng/L [36]. UV treatment removes NDMA effectively, but the cost for the amount of UV radiation required for removal is extremely high and beyond what is needed for ordinary disinfection [36]. New research into NDMA development and removal is needed to assist WWTPs in dealing with high plant effluent NDMA levels.

Environmental Fate

Studies conducted on metam sodium in aqueous solutions indicate that it is an unstable compound in surface waters that readily volatilizes to methylamine and MITC [4]. Studies indicate a half-life in water of about 30 hours in environmental conditions of pH 5-9 and 25-40 oC [4]. Under simulated sunlight UV conditions, in neutral waters at STP, metam sodium had an observed photolysis half-life of 1.6 hours [4]. Photolysis produced all the previously mentioned byproducts in water but accounted for little measurable breakdown in soils [4]. Volatilization and hydrolysis are the primary modes of transformation for metam sodium compounds in soil [4].

As a non-selective biocide, metam sodium is toxic to all non-target forms of life. Non-target plant-life degradation can lead to eutrophication, which kills fish. At an acute oral level to birds, metam sodium is considered moderately toxic with an LD50 to most birds of 211 mg/kg [21]. MITC is also highly toxic to fish and aquatic invertebrates at an LD50 ~53 ppb [21]. To mammals, oral ingestion of MITC is highly toxic with an LD50 of 55 mg/kg on an acute basis of exposure [21]. Chronic toxicity for MITC is not considered to be of great concern for aquatic forms of life because MITC volatilizes from surface waters rapidly [21]. Avian acute toxicity testing for MITC has not yet been performed [21].

Metam Sodium/MITC—Toxicology and Bioassay Testing

Acute Toxicity

Oral rat studies show absorption of 85%-90% for metam sodium applied doses within a 24 hour period [4]. Within those 24 hours, 33-54% of the ingested dose was excreted in urine and <1-3% in the feces [4]. A range of <1%-24% of ingested metam sodium was released via air expiration [4]. Orally ingested MITC doses experienced faster rates of excretion with 80-83% released in urine and <1-2% in feces [4]. Tissue binding of metam sodium (1%-2% of applied dose) was observed in rats at 168 hours of monitoring—with chemical build-up occurring in the thyroid, liver, kidneys, blood, and adrenals [4]. Rat oral LD50 values of 781 mg/kg were observed [4]. Acute oral rat testing produced vaginal bleeding, oral staining, decreased body weight, decreased food consumption, suppression of fetal body weight gain, depression, reduced activity, discoloration and thickening of internal organs, cysts on lungs and kidneys, and delayed fetal skeletal formation—with an associated NOEL for these effects of 20 mg/kg [4]. Dermal absorption in rats was observed at 2.5% of the applied dose in 1 hour at a dose of 8.6 µg/cm2 [4]. Rabbit dermal LD50 values of 1050 mg/kg were observed with symptoms like mottled liver and thymus, necrotic liver, and stomach hemorrhages. In

rats, inhalation led to respiratory irritation, eye discharge, congested and mottled lungs, liver edema, crying, spasms, and exophthalmos, but overall testing results, while indicative of toxic inhalation impacts, are conflicting amongst different species [4]. The rat inhalation studies yielded four-hour LC50 values of 2.2 mg/L [4]. Metam sodium was observed to have mild eye irritation properties in animals and four of five positive guinea pig tests indicate that metam sodium in a dermal sensitizer in guinea pigs [4].

Chronic Toxicity

A 90-day oral gavage study in dogs resulted in severe hepatitis in all animals at 10 mg/kg/day and mild hepatitis at 5 mg/kg/day [4]. In the liver, pale coloration and collapsed hepatic cords was observed in these dogs [4]. Ninety day mouse drinking studies yielded a NOEL of 0.79 mg/kg/day based on liver damage and liver necropsy findings [4]. Overall, gavage and drinking water testing on mice and rats show: stomach ulceration, decreased body/liver weights and decreased consumption—with nasal epithelial atrophy in rats present [4]. It should by noted that the primary chronic result in rats, weight loss, correlates with reduced water consumption as a direct result of water unpalatability for rats [4]. Rat studies also observed reduced hind leg function—correlating to observed muscle myopathy [4]. Ninety-day rat inhalation studies determined a NOEL of 1.11 mg/kg/day based on liver effects at 7.71 mg/kg/day. Tumors, primarily vascular, were observed at higher rates in male species over females [4]. In mice, incidences of malignant vascular tumors and angiosarcoma in several organ systems (liver/spleen) were highly significant over controls [4]. Angiosarcoma was the leading cause of death in mice [4]. Due to the results of testing in mice and rats, metam sodium is considered a potential vascular oncogen in humans [4]. Based on the occurrence of tumors found during chronic animal testing, the EPA lists metam sodium as a B2 (probable human) carcinogen [4].

Developmental and Reproductive Toxicity

In metam sodium rabbit studies, early resorptions at 4.2 mg/kg/day and fetal malformations at 42.2 mg/kg/day were observed [4]. Similar tests in Wistar Rats at 60 mg/kg/day observed skeletal malformations in young rats [4]. MITC is not considered a developmental toxicant since rat studies reveal toxicity effects more related to maternal effects [4]. Additional rat studies observed no significant reproductive effects and, as a result of testing, MITC is not considered to be a reproductive toxicant [4].

Teratogenic and Mutagenic Toxicity

Metam sodium is a clastogen in both in vivo (hamster) and in vitro (human lymphocytes). Salmonella typhimurium strains exposed to various levels of metam sodium indicated no evidence for mutagenicity; however, Chinese hamsters dosed with 42.2% aqueous metam sodium exhibited chromosomal aberrations at 600 mg/kg [4]54. Direct bone marrow toxicity is suggested by poor chromosomal quality at doses of 900 mg/kg in hamsters [4].

Metam Sodium/MITC—Health Effects to Residents, Bystanders, and Occupational Personnel

Analysis of the 1991 Cantara Loop spill and the medical incidents following the report provide the greatest sources of information regarding the health effects of metam sodium exposure to humans.

On the night of the spill, many nearby residents slept with their windows open and reported the acute onset of irritative respiratory symptoms, nausea, and headaches [20]. Over 700 residents were seen and evaluated in the days following the spill and 14% experienced skin rashes—with most of those skin rash cases involving inmates who cleaned up dead fish along the river [20]. The majority of the cases from the 1991 spill were from residents and bystanders [20]. Of the 705 recorded medical cases following the spill, 70.6% were from Dunsmuir, 7.2% from Mt. Shasta, and 6.4% were from Castelle—the three closest communities to the incident [25]. A case study on specially-selected medical records for 197 patients with symptoms believed to be induced from the spill was conducted [20]. Medical records eligible for analysis had to have reported acute symptoms within 24 hrs of exposure to the spill and the patients had to live within 1 mile of the spill and be within 1 mile of the site at the time of the accident [20]. Several patients with no history of asthma developed irritant-induced asthma meeting RADS criteria from MITC exposure directly related to the spill [20]. Worsening of existing asthma lasted in several patients for more than a three month period [20]. Until 1994, there have been no recorded occurrences of RADS from non-occupational exposures to chemicals [20]. The 1991 spill at Cantara Loop resulted in several cases of respiratory disorders in residents and occupational personnel as a direct result of exposure to the breakdown products of metam sodium—all disorders meeting the definition of RADS [20]. Forty-eight of the selected 197 patients were identified with persistent respiratory effects—20 with irritant-induced asthma (RADS), 10 with exacerbated asthma, and a relatively equal number of both sexes among the injured with asthma symptoms [20]. In general, the selected medical records observed the following acute symptoms of exposure: eye irritation and respiratory tract irritations (coughing, wheezing, dyspnea) [20]. Acute symptom rates were the highest in people living within 300 ft of the river, but were still substantially high for those up to 1500 feet away [25]. In one notable occupational exposure, a worker exposed downstream 1.5 miles from the spill for 6.5 hrs after the spill experienced burning in the eyes, chest, and nose after watching dead fish float along the river [20]. As time progressed, he experienced nausea and vomiting followed by the remainder of the acute symptoms within 5 day of exposure [20]. Exact concentrations of metam sodium or its byproducts during the period of peak exposure following the spill are not known, but air monitoring days after the spill detected 4-5 ppb on the 4th-6th days after the spill [20]. Short term water exposures are estimated to be 140-1600 ppb, but they cannot be confirmed [20].

As a result of the 1991 medical cases treated following the metam sodium spill in the Sacramento River, MITC is concluded to be irritating to eye and respiratory tissue [4]. An MITC concentration in water of 5500 ppb was detected at Antler's Campground 59 hours after the initial accident, but this concentration reduced to 8 ppb six days later [26]. Human studies using specially designed goggles resulted in the establishment of an acute eye irritation NOEL of 220 ppb with a lowest observable effect level (LOEL) at 800 ppb [4]. Monitoring of MITC concentration levels under occupational scenarios revealed that reference exposure levels are often exceeded—leading to potential health problems [4]. Human health risk assessments state that 22 ppb or greater of MITC for a 1 to 8 hr period of exposure similar to occupational conditions is enough to raise health concerns [21].

Most studies indicate that metam compounds are toxicity category III or IV eye irritants. Dermal studies produce severe to mild effects ranging from the category I to IV range [4]. The recent EPA re-registration eligibility decision (RED) for metam sodium products concludes that metam sodium is hazardous to bystanders and occupational personnel in mass due to off-site drift [24].

Metam Sodium/MITC—Recent EPA Regulation Updates for Metam Sodium Products

With the completion of the RED for metam sodium products came additional regulations on metam sodium use that went into effect on January 1, 2010 [21]. Metam sodium products must now be applied in closed, drip-free applicators to mitigate exposure to personnel. For sewer use, the product cannot be pumped within 50 feet of an access manhole [22]. In regards to WWTPs, applicators must warn wastewater treatment plants of metam sodium applications and application amounts because applications can disrupt biological wastewater treatment processes [21].

New regulations on personal protection have been established to protect workers. Applicators must now wear coveralls over one layer of clothing, use full-face respirators that are NIOSH-approved, continually rinse the applicator hose with water, and wear chemical resistant shoes with chemical resistant socks and chemical resistant gloves. Additionally, support personal and municipal inspectors should have the same personal protection equipment available in the event of a spill or emergency [21].

As of January 1, 2010, USEPA is requiring the following testing on Metam Sodium or its byproducts: 1.) measure encountered dermal exposures by applicators; 2.) determine levels of applicator exposure to MITC; 3.) conduct further reproductive and carcinogenicity tests; 4.) perform acute toxicity product analysis on individual products; 5.) perform a chemistry analysis for the presence of nitrosodiumethylamine (NDMA) in metam sodium products; and 6.) determine if MITC is carcinogenic through inhalation studies on mice/rats [21]. The continued allowable use of metam sodium is contingent on acceptable outcomes from the newly required testing.

To protect bystanders, the EPA is now requiring that posted signage be placed in public view to warn of soil fumigant operations not related to sewer use [27]. Finally, the EPA is requiring that metam sodium information be supplied to medical first responders [27]. The EPA reserves the right to cancel its RED decision at any time.

Dichlobenil—Fate and Environmental Impact

Dichlobenil tends to be slightly to moderately persistent in sediments, with tests suggesting persistence between 63 to 189 days in ponds and 126 to 312 days in muddy sediments [28]. In soils, dichlobenil is highly persistent, as tests have measured dichlobenil residues five years after application [28]. In general, studies have found significant amounts of soil persistence years after original application. Extreme persistence in soil and water tends to occur in colder climates where volatilization of dichlobenil is inhibited [30, 35]. In one case, a pond in Denver, Colorado experienced noticeable water concentrations of dichlobenil beyond 189 days after application due to the colder climate [35]. Dichlobenil was found to contaminate groundwater with an estimated persistence in groundwater of about three years or more [28]. The EPA is now requiring groundwater contamination warnings on dichlobenil-containing products to help mitigate the groundwater hazard [28]. When located in soil or water, volatilization is the primary fate of dichlobenil—making it a potential hazard for localized air contamination.

As a non-selective plant killer, dichlobenil poses a threat to non-target plant life. Unlike diquat dibromide, dichlobenil is taken up by exposed roots and spreads throughout the entire plant [28]. It

is a strong inhibitor of cellular functions in plants. The creation of cellulose synthetase, an enzyme that creates cellulose from glucose, is prevented by dichlobenil [28]. Furthermore, the inhibition of cell plate development ceases cell division—ultimately killing the plant [28]. The chemical's breakdown products also prevent important biological processes by preventing ATP from forming. ATP supplies cells with their energy to function and repair themselves [28]. This particular inhibition aids in explaining the toxicity of dichlobenil in animals.

Pond testing has served as an excellent example of the potential risks posed by the release of non-selective herbicides into the environment. In Pensacola, Florida, ponds were treated with wettable powder of dichlobenil to achieve an aqueous concentration of 1 ppm that killed nearly all benthic plant life and 80% of chara [34]. When compared to a control pond 50 m away from the treated pond, differences in oxygen production were very much apparent. Phytoplankton contributed up to 25% of the Oxygen production in the untreated pond, but nearly 100% in the treated pond, simply due to the eutrophication caused by decaying plant life [34]. It was discovered that phytoplankton play a major role in the maintenance and return to normal conditions following dichlobenil applications to ponds and that dichlobenil has little effect on such plankton except at high concentrations [34].

When ingested, the metabolite of dichlobenil is 2,6-dichlorobenzamide (BAM) [30]. Dichlobenil bioaccumulates in fish tissue, reduces the reproductive success of fish, and has been found to be acutely toxic to fish [28]. Two ppm for 10 days has been found to kill fish [28]. Rainbow trout are particularly sensitive—with a 4-day LC50 of 5 ppm [28]. Similar tests for other fish found LC50 values in the 6-16 ppm range [28]. Fish, in general, observed reduced red blood cell counts and liver damage in the form of tumors [28]. Dichlobenil has been found to affect bluegill reproduction [28]. Bioaccumulation reaches concentrations 40 times above water concentrations [28]. Olfactory damage has been observed in the nasal lining in frogs [28]. In Invertebrates, acute toxicity varied, but sand fleas, water fleas, and stonefly nymphs observed LC50 values of 1.5, 3.7, and 4.4 ppm [28]. LC50 values of less than 20 ppm were observed in mayflies, amphipod crustaceans, caddis flies, midges, and various forms of shrimp [28]. A study on pacific salmon and steelhead concluded that dichlobenil will not have a direct effect on these particular fish [31]. Chronic reproductive effects on freshwater fish and invertebrates were observed at 0.33 ppm and 1.0 ppm, of dichlobenil, respectively [31]. Similar effects for BAM were recorded at 18 and 320 ppm for fish and invertebrates, respectively [31].

Compared to the highly effective herbicidal nature of metam sodium and diquat dibromide, dichlobenil is only moderately effective when used alone, but can be highly effective when used in conjunction with metam sodium [29]. Thus, when used in Sanafoam Vaporooter, a dual environmental threat from metam sodium and dichlobenil exists. Additionally, the unique effects that the dichlobenil portion of Vaporooter may have on the environment could be exacerbated since mixture with metam sodium strengthens dichlobenil's pesticide properties.

Dichlobenil—Toxicology and Bioassay Testing

Acute Toxicity

Oral testing of dichlobenil on animals yielded LD50 values of 500 mg/kg in guinea pigs, 2000 mg/kg in mice, and 4250 mg/kg in rats [28]. If humans were to experience the same toxicological effects

as guinea pigs, a lethal dose of dichlobenil is just over one ounce for a 60 kg human [28]. Dermal and injected LD50 values ranged from 600-1350 mg/kg depending on species [28]. Concentrations of 250 mg/m3 in rats were enough to be lethal through inhalation [28]. In animals, 86-96% of all fed or injected doses of dichlobenil were excreted within 7 days—during which time low doses easily absorbed in the gastrointestinal tract while high doses accumulated in the liver [32]. Corneal lesions, iris inflammation, and conjunctive irritation were observed through rabbit studies, but washing of the eyes with water mitigated these responses [28].

Chronic Toxicity

Dichlobenil ranks as one of the most toxic chemicals to nasal tissue—causing reductions in sensory smell and transportation of the amino acid Taurine to the brain [28]. Dichlobenil targets lining of the nasal cavity—which contains enzymes that convert dichlobenil to a toxic form [28]. Irreversible binding of dichlobenil to olfactory tissue has been observed in mice and observed regeneration of olfactory damage was minimal after several weeks [28]. Human olfactory tissues contain the same enzyme that produces the toxic form of dichlobenil and threats of olfactory damage exists for all applicators of dichlobenil [28]. Olfactory damage has been observed in mice that have been subjected to dermal exposure of dichlobenil at amounts similar to accidental occupational splashes on humans or extended human exposure to granular dichlobenil [28]. Taurine transportation in mice took up to 8 weeks to return to normal levels [28]. It should be known the inhibition of Taurine transport to the nervous system is linked to Alzheimer's disease [28]. Research has concluded that nervous system damage from dichlobenil is likely to be permanent [28].

In 3-6 month exposures, the following effects were observed: Rats experienced liver degeneration and necrosis, increased liver weights occurred in dogs, "adverse" liver effects developed in mice, hamsters experienced increased liver weights and swollen liver cells, gall bladder stones developed in hamsters, and rabbits incurred weakness and loss of activity [28]. Long term rat feeding studies yielded decreased weight gain, decreased food consumption, increased kidney and liver weight, kidney degeneration, abnormalities of liver cells, and kidney stones [28]. Long term dog feeding studies observed increased liver and thyroid weights and degeneration of liver veins [28]. Finally, long term hamster feeding studies resulted in enlargement of liver cells, excessive cellular growth, and hepatitis [28]. Of the selected animal studies reviewed, liver degeneration and/or impairment seemed to be a clear symptom of exposure in all test species.

Chronic exposures to dichlobenil have led to increased cancer risks in animals. Pancreatic cancer tended to develop in hamsters, while mice and rats observed lymphoma, lung/liver cancer, and mesothelioma [28]. Dichlobenil has caused cancer and tumors in the livers of rats, male hamsters, and mice [28]. Animal studies in general have led the EPA to list dichlobenil as a possible human carcinogen as it has increased the incidence of cancer in rats, hamsters, and mice [28].

Developmental and Reproductive Toxicity

In both male and female animal testing, Dichlobenil was found to affect reproduction—thus confirming the reproductive toxicity in dichlobenil. Extended term feeding tests on hamsters resulted in decreased testicular weights, reduced seminal fluid production, tubular degeneration of testes, decreased sperm counts, and prostate degeneration [28]. Female rabbits and female rats undergoing

extended term feeding tests experienced increased occurrences of unsuccessful pregnancy and birth defects such as: cleft palate, skeletal malformation, and missing digits [28]. Developmental toxicity in newborns was observed in the form of supernumary thoracic ribs, bodily deformation, and skeletal defects in rabbits and rats [30].

Teratogenic and Mutagenic Toxicity

In a multitude of mutagenic tests, dichlobenil did not demonstrate potential for mutagenicity [30]. Additional mutagenicity tests need to be performed to confirm a lack of dichlobenil mutagenic toxicity.

Dichlobenil—Health Effects to Residents, Bystanders, and Occupational Personnel

In humans, dichlobenil can burn or irritate the skin and eyes, cause irritation of the respiratory system, headaches, dizziness, coma, severe chemical-induced acne, loss of the sense of smell, and death [33]. For oral, dermal, and inhalation exposure, dichlobenil and BAM (for oral only) have been placed in Toxicity Category III [30]. It has been concluded that dichlobenil is not a skin sensitizer—placing dichlobenil in Toxicity Category IV for these effects [30].

Acute intestinal and respiratory irritations are confirmed symptoms to direct ingestion or inhalation exposure to dichlobenil-containing products [28]. In general, acute dichlobenil exposure may lead to burning or irritation of the skin and eyes, irritation of the respiratory system, headaches, dizziness, coma, and death [33]. BAM has no toxicological concern for acute exposure, according to the EPA [30]. Chronic exposure animal studies indicate a cancer risk to humans in the liver and body cavity. The limited evidence for carcinogenicity in animal testing has led the EPA to classify it as a Group C carcinogen [30]. Currently, there is also evidence for reproductive harm to humans [33].

Dichlobenil is readily absorbed through the skin and may lead to various forms of dermatitis [33, 28]. Chloracne, a severe acne characterized by hundreds of erupting skin lesions, has been observed in human workers who have close contact to the granulated form of dichlobenil [28]. Draining, antibiotics, UV treatment, and washing did nothing to reverse the effects of chloracne, but removal from the environment was observed to work [28]. Animal studies indicate high potential to harm human kidneys and the liver [33].

No occupational exposure limits have been established by any agency for dichlobenil [33]. As a potential carcinogen, any exposure should be handled with caution. Dichlobenil, as used in Vaporooter, may produce health effects to bystanders that are more severe than the effects of dichlobenil acting alone. This is due to the increased efficacy of dichlobenil and metam sodium acting together in herbicidal applications.

References

1. Randall CW, Cokgot EU, Kisoglu Z, Punrattanasin W, Erdal U, Sriwiriyarat T. The Effects of Diquat Dibromide on Biological Wastewater Treatment Plants. Journal of Environmental Science and Health, Part A—Toxic/Hazardous Substances & Environmental Engineering Vol. A38, No. 10, 2003. p. 2453-2463

2. Siemering G, Hayworth JD, Greenfield B. Assessment of Potential Aquatic Herbicide Impacts to California Aquatic Ecosystems. Arch Environ Contam Toxicol. 2008. p.1-17

3. Municipal Sales, A Root and Grease Company. Sanafoam Vaporooter. Available from: http://municipalsales.net/sanafoam_5gal.html

4. Rubin AL. Metam Sodium (Sodium N-Methyldithiocarbamate) Risk Characterization Document. Medical Toxicology Branch, Department of Pesticide Regulation, California Environmental Protection Agency, 2004. p. 1-120

5. US Environmental Protection Agency Office of Pesticide Programs. 2008. Reregistration Eligibility Decision (RED) for Methyldithiocarbamate Salts—Metam Sodium/Potassium and MITC [Internet]. p. 1-142. US EPA. Available From: http://www.epa.gov/oppsrrd1/REDs/metamsodium-red.pdf

6. Jennings P. Memorandum: Evaluation of Potential Impacts to Wastewater Treatment Plant Microorganisms Following Application of Pesticide Products Containing Metam Sodium as an Active Ingredient to Control Intrusion of Roots into Sewage Collection Pipes and Storm Drains. United States Environmental Protection Agency. 2009. p.1-18 [Internet] Available from: http://www.rootcontrolfacts.com/uploads/EPA_MetamSodium-WWTPImpactEval_Page15.pdf

7. Yeung CH, Criddle C. Inhibition of Activated Sludge Nitrification by Root Control Chemicals: An Initial Evaluation of Dosage and Contact Time. Department of Civil and Environmental Engineering, Stanford University. 2007. p. 2-12.

8. Nitrification Inhibition Analysis for Sanafoam Vaporooter II: Summary Report. Great Lakes Environmental Center, 2007. [Internet]. p. 1-7. Available from: http://municipalsales.net/pdf/hrsdnitrification.pdf

9. EXTOXNET: Extension Toxicology Network. Pesticide Information profiles. Diquat Dibromide. 1996 [cited 2010 Jan 12] Available from: http://extoxnet.orst.edu/pips/diquatdi.htm

10. EPA R.E.D. Facts: Diquat Dibromide. United States Environmental Protection Agency. 1995 [Internet]. [Cited 2010 Jan 12] p. 1-10. Available from: http://www.epa.gov/oppsrrd1/REDs/factsheets/0288fact.pdf

11. Appendix III-Diquat. The Commonwealth of Massachusetts. The Massachusetts Department of Agricultural Resources. 2009. [cited 2010 Jan 12] p. 1-20. Available from: http://www.mass.gov/agr/pesticides/aquatic/docs/diquat.pdf

12. Diquat Dribromide. Thurston County Health Department, Olympia, Washington. 2009 [cited 2010 Jan 12] p. 1-3. Available from: http://www.co.thurston.wa.us/health/ehipm/pdf_aqua/aquatic%20actives/Diquat%20dibromide.pdf

13. Toft P. Diquat in Drinking Water. World Health Organization. 2004. [cited 2010 Jan 12] p. 1-5. Available From: http://www.who.int/water_sanitation_health/dwq/chemicals/diquat.pdf

14. Hickox H. Public Health Goals for Chemicals in Drinking Water: Diquat. California Environmental Protection Agency. 2000. [Cited 2010 Jan 12]. P. 1-18. Available from: http://www.oehha.ca.gov/water/phg/pdf/diquat.pdf

15. Review Report for the Active Substance Diquat. European Commission. Directorate-General Health and Consumer Protection. 2001. [Cited 2010 Jan 12] p. 1-19. Available from: http://ec.europa.eu/food/plant/protection/evaluation/existactive/list1_diquat_en.pdf

16. Siemering G, David N, Hayworth J, Franz A. Aquatic Pesticides Monitoring Program Literature Review. San Francisco Estuary Institute. 2005. [Cited 2010 Jan 12]. P.45-57. Available from: http://www.sfei.org/apmp/reports/71_APMP_litreview_FINAL.pdf

17. Cochran R. Diquat Dibromide: Risk Characterization Document. Medical Toxicology and Worker Health Safety Branches, Department of Pesticide Regulation, California Environmental Protection Agency, 1994. p. 1-35.

18. Sewalk CJ, Brewer GL, Hoffman D. Effects of diquat, and aquatic herbicide, on the Development of Mallard Embryos. Journal of Toxicology and Environmental Health, Part A. 2001. p. 33-45.

19. Hazardous Substance Fact Sheet. New Jersey Department of Health and Senior Services. 2001 [Cited 2010 Jan 12] p. 1-6. Available from: http://nj.gov/health/eoh/rtkweb/documents/fs/0808.pdf

20. Cone JE, Wugofski L, Balmes JR, Das R, Bowler R, Alexeeff G, Shusterman D. Persistance Respiratory Health Effects After a Metam Sodium Pesticide Spill. Chest, Official Publication of the American College of Chest Physicians. 1994. P. 500-508.

21. Reregistration Eligibility Decision (RED) for Methyldithiocarbamate Salts – Metam Sodium/Potassium and MITC. United States Environmental Protection Agency. 2008. [Cited 2010 Jan 12] p.1-141. Available From: http://www.epa.gov/oppsrrd1/REDs/metamsodium-red.pdf

22. Fact Sheet: EPA Regulates Metam Sodium Sewer Use. Root Control Facts. 2009. [Cited 2010 Jan 12]. Available from: http://www.rootcontrolfacts.com/uploads/Fact%20Sheet%20Metam%20Sodium%20%282%29.pdf

23. NDMA Source Control: Sources of N-nitrosodiumethylamine in the Orange County Sanitation District Service Area. Orange County Sanitation District. 2002. [Cited 2010 Jan 12]. Available from: http://www.rootcontrolfacts.com/uploads/OrangeCountyNDMAResearch_RootControl.pdf

24. Blondell J. Memorandum: Review of Metam Sodium Incident Reports. United States Environmental Protection Agency. 2003. [Cited 2010 Jan 12] Available from: http://www.rootcontrolfacts.com/uploads/EPA_MetamSodiumIncidentReview_Conclusion.pdf

25. Kreutzer R. Acute Health Effects of the Cantara Metam-Sodium Spill: An Epidemiological Assessment. Environmental Health Investigations Branch. California Department of Health Services. 1992. p. 1-3. [Cited 2010 Jan 12] Available from: http://www.ehib.org/papers/22_Kreutzer_1992_Acute.pdf

26. Segawa RT, Marade SJ, Miller NK, Lee PY. Monitoring of the Cantara Metam-Sodium Spill. Department of Pesticide Regulation. US Environmental Protection Agency. 1991.

27. Sissel K. EPA Strengthens Restrictions on Five Common Pesticides. Chemical Week. 2008. Vol. 170, Iss. 22, p. 33

28. Cox C. Dichlobenil: Herbicide Fact Sheet. Journal of Pesticide Reform, Vol. 17, No. 1. 1997. [Cited 2010 Jan 12] p. 14-19. Available from: http://www.pesticide.org/dichlobenil.pdf

29. Ratnayake S. Memorandum: Alternative Assessment on Root Control Use of Metam Sodium in Sewer Lines. United States Environmental Protection Agency. 2008. [Cited 2010 Jan 12] Available from: http://www.rootcontrolfacts.com/uploads/pdfs/EPA_RootControlAlternativesAssessment.pdf

30. EPA R.E.D. Facts: Dichlobenil. United States Environmental Protection Agency. 1998. [Cited 2010 Jan 12] p.1-13. Available from: http://www.epa.gov/oppsrrd1/REDs/factsheets/0263fact.pdf

31. Stavola A, Turner L. Dichlobenil: Analysis of Risks to Endangered and Threatened Pacific Salmon and Steelhead. Environmental Field Branch, Office of Pesticide Programs. 2003. p. 1-31.

32. Dichlobenil: Roadside Vegetation Management Herbicide Fact Sheet. Washington State Department of Transportation. 2006. [Cited 2010 Jan 12] p.1-4. Available from: http://www.wsdot.wa.gov/NR/rdonlyres/37DC03D2-3E93-4A36-AF6A-F08066A3A6BB/0/dichlobenil.pdf

33. Hazardous Substance Fact Sheet. New Jersey Department of Health and Senior Services. 2000 [Cited 2010 Jan 12] p.1-6. Available from: http://nj.gov/health/eoh/rtkweb/documents/fs/0636.pdf

34. Walsh G, Miller C, Heitmuller PT. Uptake and Effects of Dichlobenil in a Small Pond. Bulletin of Environmental Contamination and Toxicology, Vol. 6, No. 3. US Environmental Protection Agency. 1971. p. 279-288.

35. Cope OB. McCraren JP, Eller L. Effects of Dichlobenil on Two Fishpond Environments. Weed Science, Vol. 17, No. 2. Weed Science Society of America. 1969 p. 158-165.

36. Sedlak DL, Deeb RA, Hawley EL, Mitch WA, Durbin TD, Mowbray S, Carr S. Sources and Fate of Nitrosodimethylamine and its Precursors in Municipal Wastewater Treatment Plants. Water Environment Research, Vol. 77, No. 1. 2005. p. 32-38.

37. Bioaccumulation. Toxic Substances Hydrology Program. USGS. 2006. [Cited 2010 Jan 25] Available from: http://toxics.usgs.gov/definitions/bioaccumulation.html

38. Marer, P. 1996. Sewer Line Root Control. A Publication of the Pesticide Education Program. University of California, Division of Agriculture and Natural Resources