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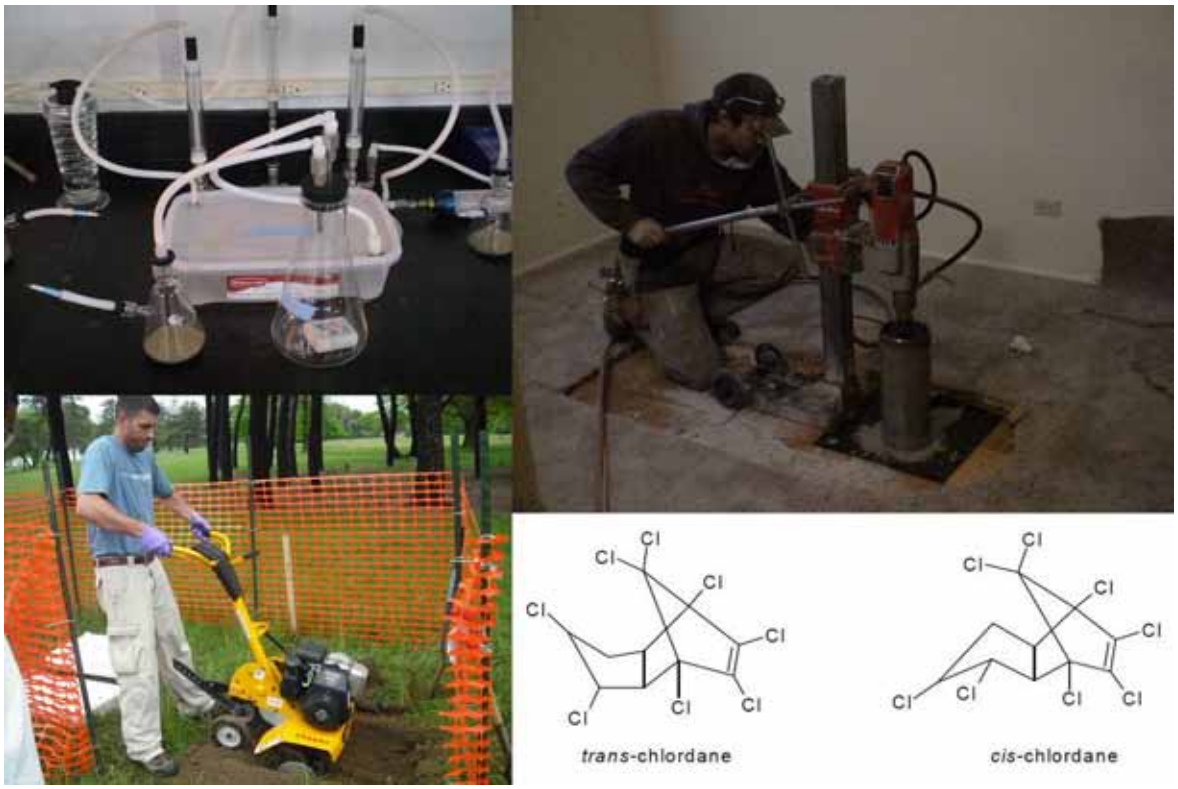
Evaluation of Volatilization Potential for Legacy Chlordane in Military Housing Area Soils

Scott A. Waisner, Victor F. Medina, Michael A. Jones, and Catherine C. Nestler

October 2011



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Evaluation of Volatilization Potential for Legacy Chlordane in Military Housing Area Soils

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Final report

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Abstract: The U.S. Air Force used the chlorinated pesticide, chlordane, to control termites around base housing until it was banned in 1988. As bases are closed, contracted, or realigned, soil issues associated with this pesticide must be addressed. One issue that is not well understood is chlordane volatility. There are documented cases where chlordane applied to soil resulted in vapor intrusion into buildings; however, these cases all involved freshly applied pesticides. The effect of aging and weathering for at least 20 years would likely change the potential for volatilization of soil-applied chlordane.

This report documents three studies to assess volatility of aged chlordane in soil. The first study was a laboratory study in a forced air system. Soils studied included chlordane-contaminated soils from McGuire Air Force Base (AFB), Davis-Monthan AFB, and a reference soil from the Vicksburg, MS, area called WES soil. Tests of the various soils conducted at 20 °C and 50% RH indicated that of these, only the Davis-Monthan soil, which had the highest chlordane concentration and the lowest total organic carbon concentration, had a measurable chlordane flux.

The second study, conducted in the field at Fort Dix Army Base, evaluated the effect of soil disturbance. This included simple vegetative removal, disturbance of the soil by tilling, and coring into the soil. Chlordane was found in all the sample locations and depths, with higher concentrations being found in deeper core samples. However, volatile chlordane was only detected in the borehole sample immediately after the hole was created.

The last study was conducted at Mountain Home AFB and investigated volatility under slab foundations of housing at the base. Four different housing types were tested. Indoor air sampling was conducted in each housing unit tested. This was followed by sampling of the sub-slab atmosphere by drilling holes through the foundation. Cores were then drilled through the foundation, and soil samples from below the slab were collected and analyzed for chlordane. No chlordane was found in the indoor air, sub-slab soil vapor, or the sub-slab soil samples at any of the housing units tested.

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Preface

This report results from experimental work conducted from 2009 to 2010. The purpose was to investigate the volatility of chlordane in aged soils during excavation and under buildings. The project was a team effort between the US Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL) and Applied Research Associates, Inc. (ARA). The project was funded by the Air Force Center for Engineering and the Environment (AFCEE) via two mechanisms. Initial funding was through a broad agency announcement for which ARA served as the lead organization and ERDC received funding through ARA by a cooperative research and development agreement. Additional funding was then provided directly to ERDC from AFCEE via a military interdepartmental purchase request.

This research effort was directed by Scott Waisner with technical oversight from Dr. Victor F. Medina, both of the Environmental Engineering Branch (EP-E), Environmental Processes and Engineering Division (EP), ERDC-EL. This report was prepared by Waisner with assistance from Dr. Medina and Catherine Nestler and Mike Jones, both of ARA. Dr. Heather Smith and Dr. David Johnson provided ERDC in-house review. Beattie Williams (ARA) provided project management oversight.

This study was conducted under the direct supervision of Deborah Felt, Acting Chief EP-E, and under the general supervision of Dr. Richard E. Price, Chief EP, and Dr. Elizabeth C. Fleming, Director EL.

At the time of publication of this report, COL Gary E. Johnston was Commander of ERDC, and Dr. Jeffery P. Holland was Director.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
ounces (mass)	0.02834952	kilograms
pounds (mass)	0.45359237	kilograms
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters

Acronyms

AFB	Air Force Base
AFCEE	Air Force Center for Engineering and the Environment
ATSDR	Agency for Toxic Substances and Disease Registry
DIWET	Distilled Water- Waste Extraction Test
EL	Environmental Laboratory
ERDC	Engineer Research and Development Center
FDA	Food and Drug Administration
FMC	field moisture capacity
FRTR	Federal Remediation Technology Roundtable
GC-ECD	gas chromatography with electron capture detection
IRIS	Integrated Risk Information System
L/min	liters per minute
MCL	maximum contaminant level
MHAFB	Mountain Home Air Force Base
ng/Kg	nanogram of analyte per kilogram of soil (or tissue), ppt
ng/L	nanogram of analyte per liter of solution, ppt
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PBET	physiologically based extraction test
PEL	permissible exposure limit (OSHA)
SPLP	synthetic precipitation leachate procedure
TCLP	toxicity characteristic leachate procedure
TWA	time-weighted average
µg/Kg	microgram of analyte per kilogram soil (or tissue), ppb
µg/L	microgram of analyte per liter of solution
$\mu g/m^3$	microgram of analyte per cubic meter of gas
USEPA	United States Environmental Protection Agency

1 Introduction

This report details three separate but related studies. First, laboratory studies were conducted using soils with history of treatment with chlordane. This study investigated chlordane volatility from head spaces of containers with these contaminated and aged soils. Second, a field study was conducted at Fort Dix, NJ, investigating soil volatility in the field following soil disturbance that would simulate construction activities. The third study investigated the potential for soil vapor intrusion from chlordane aged on soil at Mountain Home Air Force Base, ID.

Background and objectives

Chlordane is an organochlorine pesticide formerly used for termite control around or under building foundations. This pesticide was used to treat many U.S. military housing units either before or after construction or, in some cases, both. A substantial number of housing units treated with chlordane have reached the end of their useful life and have been or are scheduled for demolition. For this reason, the fate of chlordane in the treated soils during the demolition of the housing units and in some cases the redevelopment of the areas is now of concern. Prior to demolition and/or transfer of military housing areas, chlordane soil contamination must be addressed either by cleanup or by establishing that it is of minimal risk to leave in place. For this reason, the Air Force Center for Engineering and the Environment (AFCEE) funded this study.

Earlier research conducted at the U.S. Army Engineer Research and Development Center (ERDC) (Medina et al. 2009) indicated that chlordane applied to the soil and aged was bound to an extent that it was immobile in both the natural and municipal landfill environments and not available to humans if the soil were ingested. However, these tests did show that aged chlordane was available to some plants and organisms living in the soil. It is known that freshly applied chlordane is volatile and through the process of atmospheric transport may result in vapor intrusion (USEPA 2002). However, the long-term volatility as the contaminant ages in soil has not been documented.

Demolition and construction activity in housing areas will re-expose to the atmosphere soils historically treated with chlordane, but it is unknown

whether aged chlordane on these soils remains sufficiently volatile to be of concern. It was the objective of the work conducted in this report to determine if chlordane aged on the soil poses a significant exposure risk to demolition crews or retains the potential for vapor intrusion into new buildings constructed on these soils.

Historical usage and reported problems

From 1948 to 1988 chlordane was used as an insecticide in the United States for agricultural crops and livestock, for lawns and gardens, and also for underground treatment around the foundation of buildings. In 1978, the USEPA banned the use of chlordane on food crops and phased out other above-ground uses over the following 5 years. From 1983 to 1988, chlordane's only approved use was for underground application to control termites in buildings. In 1988, all uses of chlordane in the United States were stopped (USEPA 1997). Commercial chlordane was used worldwide as an effective insecticide but has been banned worldwide since 2004 due to its toxicity and persistence in the environment. Although its use has been completely banned for 20 years in the United States, chlordane is still being detected in air, soil and groundwater samples around the world (Bidleman et al. 2004).

Six reports by U.S. Air Force and Army agencies were found documenting the use of chlordane for subterranean termite control at military housing units between the years of 1970 and 1982, which resulted in measureable indoor air concentrations of chlordane. The earliest report indicated sub-slab injections at two units with ventilation ducts located in the poured slabs where the pesticide was inadvertently injected directly into the ducts (Callahan 1970). This situation resulted in serious contamination of the air and all surfaces and materials in the residences. In 1975 pesticide odors were reported indoors following injection of chlordane at a housing unit with a cinder block foundation and ventilation ducts located in the crawl space under the unit (Olas et al. 1976). Based on chlordane concentrations found in the soil 1-1/2 to 2 years post injection, the authors hypothesized that the pesticide was either excessively or poorly applied. In 1977 a housing unit was treated with chlordane by treatment of cinder block voids and injections (Vinopal and Olds 1977). This incident resulted in the residents of the unit becoming physically ill immediately following application of the chlordane but with no apparent lasting signs of exposure. Two reports published in 1981 surveyed housing units with ventilation ducts either in or under the slab and that underwent post-construction treatment for termites

by sub-slab injection of a chlordane emulsion (Livingston et al. 1981, Lillie 1981). The results of these surveys indicated that a large majority of these units, 969, exhibited measurable indoor air concentrations of chlordane. Of these units 4% exhibited indoor air concentrations of chlordane greater than 5 μg/m^3. In the winter and spring of 1982, a total of 2,113 housing units treated with chlordane prior to construction were investigated for indoor air contamination (Lillie 1982). All of the units tested had ventilation ducts either in or below the slabs, and the soil was treated with chlordane before the slabs were poured. Only two of these units showed an indoor air concentration of chlordane above 5 μg/m^3.

Toxicology

People can be exposed to chlordane through ingestion, dermal exposure, or inhalation of vapors. Chlordane primarily affects the nervous and digestive systems causing headaches, irritability, confusion and vision problems as well as vomiting and stomach cramps (ATSDR 1994). Chlordane has been classified for carcinogenicity in humans as B2, a probable human carcinogen based on animal studies (USEPA 1997). The Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) have both set the time-weighted average (TWA) exposure limit for chlordane in the workplace environment at 0.5 mg/m^3 (NIOSH 2005). The EPA has calculated a generic indoor air screening level for chlordane of 0.024 μg/m^3 for a target cancer risk level of 10^{-6} (USEPA 2002).

Physico-chemical properties

Chlordane is sometimes referred to by the trade names Octachlor and Velsicol 1068. It is a thick liquid whose color ranges from colorless to amber, depending on its purity. It may have no smell or a mild, irritating smell. Commercial chlordane, technical grade, is a mixture of more than 140 compounds including the chlorocyclodiene compounds (Dearth and Hites 1991). Of the many related compounds, about 10 are major components including: *trans*-chlordane, *cis*-chlordane, *β*-chlordene, heptachlor, and *trans*-nonachlor. The *cis*- and *trans*- isomers of chlordane (Figure 1) make up 60-85% of the commercial mixture depending on the manufacturing process (Buchert et al. 1989). Chlordane does not dissolve in water; therefore, before it can be used as a spray, it must be placed in water with emulsifiers, which results in a milky-looking mixture. The use of chlordane in the present report refers to both the *trans*- and *cis*-chlordane isomers.

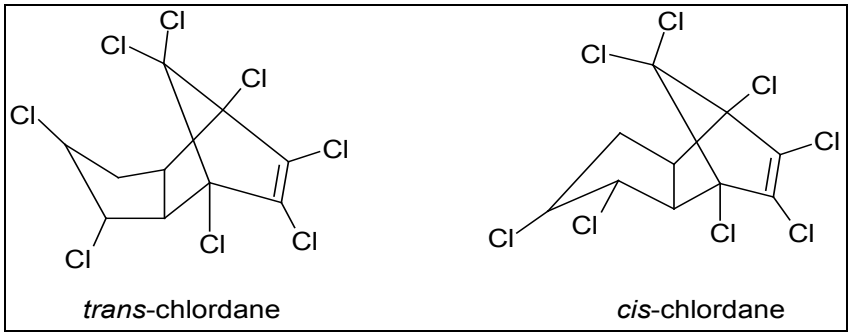

Figure 1. Structural isomers of chlordane.

The *cis*- and *trans*- isomers of chlordane are non-superimposable mirror images (i.e., chiral) and have identical physico-chemical properties. These physical and chemical properties are often difficult to specify for technical grade chlordane because it is a complex mixture (USEPA 1997). For example, the vapor pressure of the mixture will change over time since the more volatile components will be removed faster, changing the composition of the mixture. However, the ratio of chlordane isomers will remain the same since these processes are not selective for a particular isomer. This is true for all the physical processes affecting chlordane such as volatilization, hydrolysis, or photodegradation (Müller et al. 1997).

In contrast, biological processes are isomer specific and will change the ratio of *cis*- to *trans*- isomers in the soil providing a reliable test for occurrence of biodegradation (Eitzer et al. 2003, Li et al. 2007, Meijer et al. 2001). Different rates of degradation and transport among the constituents of the mixture may result in compositional changes over time. These compositional changes need to be considered when selecting a remediation option.

Chlordane is hydrophobic and binds strongly to organic carbon, clay, and silt in anaerobic sediments (Nakano et al. 2004). Previous studies have concluded that organic compounds bound to soil undergo a two-step desorption process. An initial fast exchange of a weakly bound fraction is followed by a more lengthy and slower release of a tightly bound fraction (Meijer et al. 2003). Scholtz and Bidleman (2007) have prepared a long-term predictive model of the fate of chlordane isomers in soil. The model predicts that chlordane is immobile in soil. Field data, which supports this prediction, has demonstrated that leaching is not a transport mechanism for chlordane. However, volatilization is an important route of loss of soil residues, and the rate-limiting factor is soil binding not atmospheric concentration.

2 Laboratory Tests

Laboratory tests were conducted to estimate the rate of volatilization of chlordane aged on soils and to estimate how environmental conditions may affect this rate. Tests were conducted on soils containing technical chlordane aged on soils in the field over several decades and on clean soil with chlordane applied in the laboratory and artificially aged.

Materials and methods

Soils

Soils from three different sites were used in this study. These sites included McGuire Air Force Base (AFB) in New Jersey, Davis-Monthan AFB in Arizona, and Waterways Experiment Station (WES) in Mississippi. The AFCEE arranged the collection of both contaminated and background (bkgd) soils from the two AFB sites. The soils from McGuire AFB were classified as a sandy-silt, and the soils from Davis-Monthan AFB were classified as sandy. An uncontaminated silty (loess) soil from WES was collected by ERDC. Each soil was then analyzed for total chlordane and total organic carbon (TOC). Initial characterization of these soils is provided in Table 1. Two artificially aged soils were created for this study from the WES soil: an uncontaminated artificially aged soil, WES (aged), and a freshly contaminated and artificially aged soil, WES (spiked-aged). The aging process is described in the following section.

Artificial aging procedure

For the aging process, two aluminum pans approximately 13-½ in. x 10 in. x 2-½ in. were filled with 1 L of clean WES soil. One pan of soil was spiked with a 2 mg/L solution of chlordane that had been diluted from an approximately 3:1 chlordane:water emulsification. The chlordane solution (153.5 g) was added to the soil until it was thoroughly wetted. This resulted in the application of approximately 200 µg of chlordane per kg of clean soil. The second pan of soil was saturated with deionized (DI) water (154 g) and aged as a control.

Table 1. Characterization of test soil.

Soil	Chlordane (µg/kg)	TOC (mg/kg)
McGuire AFB	2,683 ± 575 (n = 5)	1020
McGuire AFB (bkgd)	110 ± 23 (n = 3)	769
Davis-Monthan AFB	13,832 ± 568 (n = 3)	<335
WES	NA	3170
WES (aged)	0.21 ± .01 (n = 3)	NA
WES (spiked-aged)	21.3 ± 1.1 (n =3)	NA

The soils were allowed to air dry under a fume hood prior to beginning the aging process. During the aging process each pan of soil was wetted with approximately 2.3 L DI water and homogenized by hand mixing with a garden cultivator. The saturated soils were maintained at a temperature of 55 ^{o}C in an environmental chamber with mechanical convection. The soil was allowed to dryand completely dried between wettings, and the wetting and drying process was repeated a total of 18 times over a period of 90 days. The chambers were vented to the atmosphere, which most likely resulted in loss of chlordane during the weathering process, which mimics the natural process. The soils were then removed from their pans and funneled into flasks as part of the bench-scale study.

Bench-scale apparatus

This test was conducted by adding 50 g of soil to 250-mL single-side-arm shake flasks (Ace Glass #14205). The bottom diameter of the flask was 7.62 cm (3.00 in.), which provided a soil surface area of 45.6 cm^2. One flask containing only 25 mL of the 3:1 chlordane:water emulsification was also set up as a control to measure volatilization rates unhindered by the desorption process. The solution in this flask covered an area in the bottom of the flask approximately 6.35 cm (2.5 in.) in diameter, which provided a surface area of 31.7 cm^2.

Air flowed into the flask through the neck at a rate of 50 standard cubic centimeters per minute (sccm) and exited through Chromosorb-102 sorbent tubes fitted into the side arm. A schematic of the experimental apparatus is shown in Figure 2. The temperature and humidity of the flask were controlled according to the experimental matrix (Table 2).

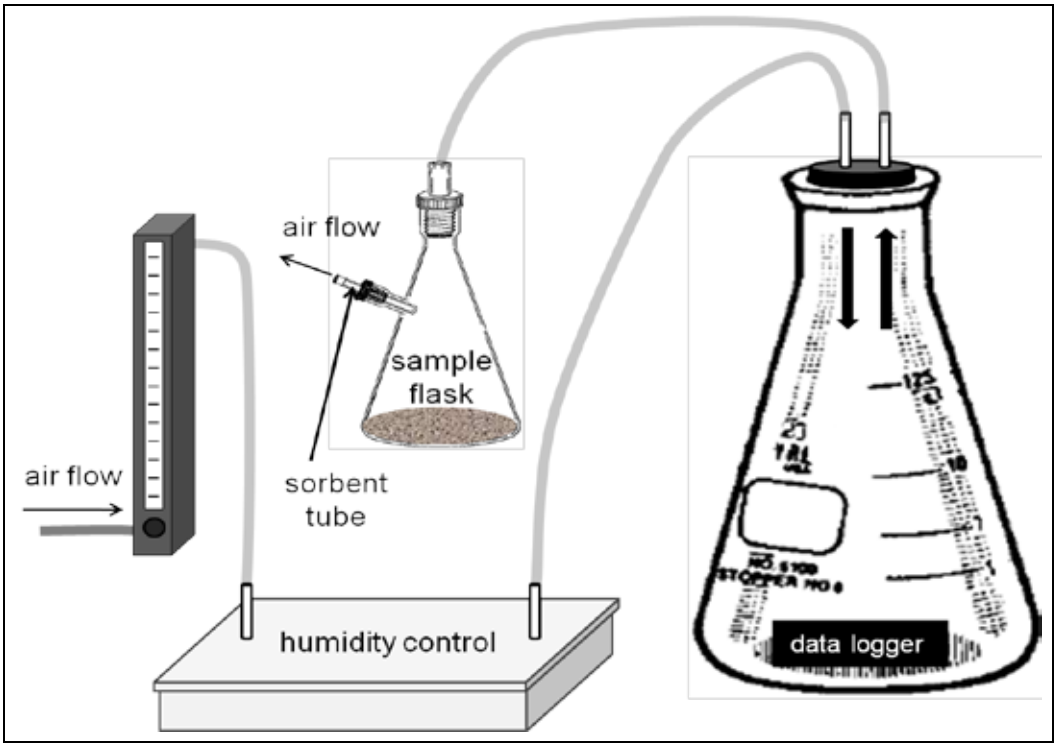

Figure 2. Schematic of bench-scale setup.

Table 2. Parameters tested (bench-scale study).

Soil Type	Temperature (°C)	% Relative Humidity	Soil Disturbance
McGuire	22	10	None
McGuire	22	50	None
McGuire	22	90	None
McGuire	22	50	Daily
McGuire	22	50	Weekly
McGuire	10	50	None
McGuire	40	50	None
McGuire	50	50	None
McGuire (bkgd)	22	50	None
Davis-Monthan	22	50	None
WES (spiked and aged)	22	50	None
WES (aged)	22	50	None

The Chromosorb-102 sorbent tubes (SKC Inc. part no. 226-49-102) were made of glass tubes with a 6mm outside diameter and 70mm long and contained two sections of Chromosorb sorbent (front = 66 mg; back = 33 mg). The two sections of sorbent were separated and held in place by

sections of packed glass wool. Chromosorb-102 tubes are listed in NIOSH method 5510 (NIOSH 2003).

Three different levels of relative humidity (RH) were established using three different control techniques placed in the flow path prior to the flasks. Drierite desiccant material in a column was used to give a low RH of about 10%. A medium level RH of approximately 50% was achieved by using a saturated salt solution of NH_4NO_3 in a plastic container. A high level RH of 90-100% was achieved by sparging air through deionized water (Figure 3).

Figure 3. Bench-scale setup.

Flasks were maintained at one of four different temperatures during the course of the experiment: 10 °C, 22 °C, 40 °C, and 50 °C. The 10 °C condition was achieved by placing the flask and humidity control device in a refrigerator maintained at 10 °C. The 40 and 50 °C conditions were achieved by placing the flasks and humidity control devices in an incubator maintained at the corresponding temperatures. All flasks tested at 22 °C were kept on a laboratory bench top where the room was maintained at 22 ± 2 °C.

Three different frequencies of soil disturbance conditions were created: either daily, weekly, or no soil disturbance. Soil disturbance was achieved by shaking the flasks by hand for approximately 30 seconds on a daily basis (5 days/week) or once per week. To limit the possibility of soil particles

being transported to the sorbent tubes, the air flow to each flask was stopped during the soil disturbance process and the dust allowed to settle prior to reinitiating air flow. This process typically required less than 5 minutes, and the break in air flow was ignored in the calculation of total air volumes collected.

Air exiting each flask passed through the attached sorbent tubes continuously between sample events to capture volatile chlordane in each flask. Samples were collected replacing the attached sorbent tube with a new sorbent tube. Sorbent tubes were capped, taped and refrigerated until delivered to the analytical lab for extraction. Sorbent tubes were exchanged on each flask on days 1, 3, 10, 30 & 90 from the initial setup of the study. This resulted in approximate air sample volumes of 72, 144, 504, 1440 and 4320 standard liters respectively and provided lower detection limits with each sampling event. The first sampling event included the addition of an extra sorbent tube in series on each flask to capture any volatiles that may have "broken" through the first tube.

Analytical methods

Air samples were collected and analyzed according to NIOSH Method 5510 (NIOSH 2003) with the exception that a cellulose ester prefilter was not used. The filter was deemed unnecessary due to the nature of the test apparatus being used and the limited possibility of particulate transport during the tests. Soil samples were analyzed for chlordane by EPA Method SW846 8081A (USEPA 1999a). All analyses for chlordane were conducted by Argus Analytical located in Ridgeland, Mississippi.

Results

To simplify the tables of results, the maximum concentration and corresponding mass transfer and flux rates are reported when chlordane was detected, and the lowest detection limit and corresponding rates are reported when no detection occurred. The complete results are provided in Appendix A.

In the study of mass transfer, flux is reported as the mass that flows through a unit area per unit time. In these results, the authors report a mass transfer rate, a specific mass transfer rate (per unit mass of soil), and a flux rate. This is done because it was not determined if the mass transfer is limited by surface area or total mass of soil in the flasks. That determination was

beyond the scope of this study. However, a shallow depth of soil in the flasks was chosen to limit mass transfer issues due to soil depth. Using a mass transfer rate specific to soil mass will likely provide a conservative estimate (higher) when extrapolated to greater thickness of soil.

Contaminant aging in soil

Based on the calculated mass of chlordane added and the analytical results of the aged soil, approximately 90% of the chlordane applied to the WES (spiked-aged) soil was lost, presumably by volatilization, but it is possible that a fraction of the chlordane applied was not recoverable by the extraction process used for analysis. Some of the lost chlordane from this soil appears to have been readsorbed to the WES (aged) soil, which was aged in the same environmental chamber. This resulted in a concentration of chlordane in the WES (aged) soil that was approximately 1/100th that seen in the WES (spiked-aged) soil. Similarly, a low concentration of chlordane was seen in the McGuire AFB (bkgd) soil, which was collected from an area not treated with chlordane but was located near an area that was treated. This observation illustrates the movement and redistribution of chlordane through the soil by volatilization and readsorption.

Effect of temperature

Four flasks with McGuire AFB soil were maintained at four different temperatures ranging from 10 to 50 ^{o}C. The relative humidity of the incoming air to all flasks was maintained at approximately 50% and the soils were undisturbed throughout the test. The chlordane concentrations in the air and mass-transfer and flux rates from the soil are provided in Table 3. No chlordane volatilization was detected for the soils maintained at 10, 22, or 40°C. However, chlordane volatilization was detected at the 90-day sample period for the soil maintained at 50°C.

Effect of relative humidity

Three flasks with McGuire AFB soil were maintained at three different relative humidity levels. The incoming air and flasks were maintained at approximately 22 ^{o}C, and the soils were undisturbed throughout the test. The chlordane concentrations in the air and mass-transfer and flux rates from the soil are provided in Table 4. No chlordane volatilization was detected for the soils maintained at 10 and 50% RH. However, volatilize-tion of chlordane was detected by the 30-day sample period for the soil

maintained at 90% RH, which is the value reported in Table 4. The concentration of chlordane in the air decreased from 0.90 to 0.52 µg/m^3 between the sample collected at the 30-day and 90-day period for this soil.

Table 3. McGuire soil vs. temperature at 50% RH.

Temperature (°C)	Concentration (µg m^{-3})	Mass Transfer (µg day^{-1})	Specific Mass Transfer (µg kg^{-1} day^{-1})	Flux (µg m^{-2} day^{-1})
10	< 0.23	< 0.02	< 0.33	< 3.7
22	< 0.24	< 0.02	< 0.34	< 3.8
40	< 0.24	< 0.02	< 0.34	< 3.7
50	0.57	0.04	0.82	9.0

Table 4. McGuire soil vs. relative humidity at 22 °C.

Relative Humidity (%)	Concentration (µg/m^3)	Mass Transfer (µg day^{-1})	Specific Mass Transfer (µg kg^{-1} day^{-1})	Flux (µg m^{-2} day^{-1})
10	< 0.24	< 0.02	< 0.34	< 3.8
50	< 0.24	< 0.02	< 0.34	< 3.8
90	0.90	0.06	1.29	14.2

Effect of soil disturbance

Three flasks with McGuire AFB soil were subjected to three different levels of soil disturbance: no disturbance, weekly disturbance, and daily disturbance. The incoming air and flasks were maintained at approximately 22 °C and 50% relative humidity. The chlordane concentrations in the air and mass-transfer and flux rates from the soil are provided in Table 5. Chlordane volatilization was not detected in any of the flasks.

Table 5. McGuire soil vs. soil disturbance at 22°C & 50% RH.

Disturbance Frequency	Concentration (µg/m^3)	Mass Transfer (µg/day)	Specific Mass Transfer (µg kg^{-1} day^{-1})	Flux (µg m^{-2} day^{-1})
None	< 0.24	< 0.02	< 0.34	< 3.8
Weekly	< 0.24	< 0.02	< 0.34	< 3.7
Daily	< 0.24	< 0.02	< 0.34	< 3.7

Effect of soil type and aging

Six different soils were tested for volatilization of chlordane. One flask containing only technical chlordane was also tested for volatilization of chlordane. The incoming air and flasks were maintained at approximately 22 °C and 50% relative humidity, and the flasks were undisturbed throughout the test. The chlordane concentrations in the air and flux rates from the soil are provided in Table 6.

Table 6. Volatilization vs. soil type and aging at 22°C & 50% RH.*

Soil	Soil ($\mu g\ kg^{-1}$)	Concentration ($\mu g\ m^{-3}$)	Mass Transfer ($\mu g\ day^{-1}$)	Specific Mass Transfer ($\mu g\ kg^{-1}\ day^{-1}$)	Flux ($\mu g\ m^{-2}\ day^{-1}$)
McGuire	2,683 ± 575 (n = 5)	< 0.24	< 0.02	< 0.34	< 3.8
McGuire (bkgd)	110 ± 23 (n = 3)	< 0.24	< 0.02	< 0.34	< 3.8
Davis-Monthan	13,832 ± 568 (n = 3)	2.65	0.19	3.81	41.8
WES	NA	< 0.24	< 0.02	< 0.34	< 3.7
WES (aged)	0.21 ± .01 (n = 3)	< 0.23	< 0.02	< 0.33	< 3.7
WES (spiked-aged)	21.3 ± 1.1 (n =3)	< 0.23	< 0.02	< 0.33	< 3.7
No Soil (technical chlordane)	3:1 chlordane:water emulsion	82.1	5.91	237*	1297

* $\mu g\ L^{-1}\ day^{-1}$

NA: not analyzed

Discussion

Results from the test of environmental factors showed that both temperature and humidity can be a factor in the rate of chlordane volatilization from soil that has been naturally aged on soil for several decades. In our laboratory tests of temperature effect at a moderate relative humidity level (50%), we observed chlordane volatilization only at the highest temperature, 50°C. This indicates that the rate of volatility is positively correlated with temperature, which is to be expected. However, even at this extreme temperature, the specific mass transfer rate measured was only 0.82 $\mu g\ kg^{-1}\ day^{-1}$. Similarly, in tests on the effect of humidity at a moderate temperature

(22°C), chlordane volatilization was only observed at the highest relative humidity level, 90%. This indicates that the rate of volatility is also positively correlated with relative humidity levels. The specific mass-transfer rate measured at 90% humidity was 1.29 μg kg^{-1} day^{-1}, which is similar to the rate observed at the elevated temperature.

Of the three contaminated soils tested, only the soil from Davis-Monthan AFB produced a measureable level of volatilization. The specific mass-transfer rate measured for this soil was 3.81 μg kg^{-1} day^{-1} at moderate temperature and humidity levels. This is 11 times higher than the specific mass transfer rate detection limit for the McGuire AFB soil, which was non-detect under similar conditions. The Davis-Monthan AFB soil contained both five-times higher levels of chlordane contamination and lower levels of TOC than the McGuire AFB soils. Both of these factors affect the sorption of most contaminants on soil and are also likely to affect the rate of volatilization of sorbed chlordane from the soil. The Davis-Monthan soil also originated from a desert climate while the other soils originated from temperate climates that receive significant rainfall.

While the measured rates of volatilization of chlordane aged on soil are quite low, the specific mass-transfer rate measured from a technical chlordane emulsion was much higher, 237 μg L^{-1} day^{-1}. The rate of volatilization from this emulsion may have been limited by the slow flow rate through the test flask, and the maximum rate of volatilization is likely to be higher under similar conditions of temperature and humidity. These levels of volatility are only likely to occur when technical chlordane solution is freshly applied to soil. This is supported by the fact that the only reported cases found in the literature of nausea or illness attributed to the use of chlordane for termite control around foundations coincided with the recent application of chlordane, as discussed on page 2 of this report.

3 Field Test at Ft. Dix

Materials and methods

Test site

Tests were conducted at Ft. Dix Army Base in New Jersey. Ft. Dix is co-located with McGuire Air Force Base, which was the source for two of the soils used in the laboratory tests. The area chosen for sampling was the former location of the Child Development Center located on Elbe Loop. Historically, chlordane was applied around the outside of the building foundation in shallow trenches. The test location chosen was near sampling stake number 50382, near N39°59'40" W74°37'33", which can be located on the map provided as Appendix B. During the site characterization conducted earlier in 2009, samples collected at this stake location provided the highest average chlordane concentration over the 3-ft depth sampled. The center of the test areas sampled was located within 6-12 in. of the former building foundation.

Field methods

Both air samples and soil samples were collected for chlordane analysis from four different types of soil disturbances to estimate potential release and exposure to volatile chlordane from the soil during future construction activities. Three different soil-disturbance scenarios were conducted at the test location to mimic normal unconfined disturbance of surface soils during construction: a scraped (denuded) soil surface, a grass root-zone, and a denuded soil tilled to a 16-in. depth. In addition, a 2-ft deep hole was bored to estimate the potential for exposure to volatilized chlordane in a shallow trench excavation. The soil core was also analyzed to establish a depth profile of chlordane contamination in the soil. An air sample from undisturbed surface soil was also collected as a control in the same manner as the shallow disturbance samples.

Surface disturbance of the tested soil was achieved by removing a grass layer approximately 1 m^2 in size. The soil was turned so the roots were facing upwards (Figure 4). Shallow disturbance was achieved by using the same technique, and the soil was tilled to a depth of 16 in. (Figure 5). The soil was tilled in flights with a rotary garden tiller and the soil was removed between flights. After reaching a depth of 16 in., the soil was replaced in the excavated hole.

Figure 4. Surface disturbance.

Figure 5. Using tiller to create shallow disturbance.

Air samples from surface and shallow disturbance were collected by placing large fiberglass trays, used as flux chambers, over the areas both during and between sampling events. Flux chambers were placed over root-zone and the freshly exposed soil areas to prevent loss of contaminant due to dispersion and advection by the wind (Figure 6). Sorbent tubes were connected to the flux chambers and sampling pump by PVC tubing. The sample train is shown in Figure 7.

Figure 6. Test site.

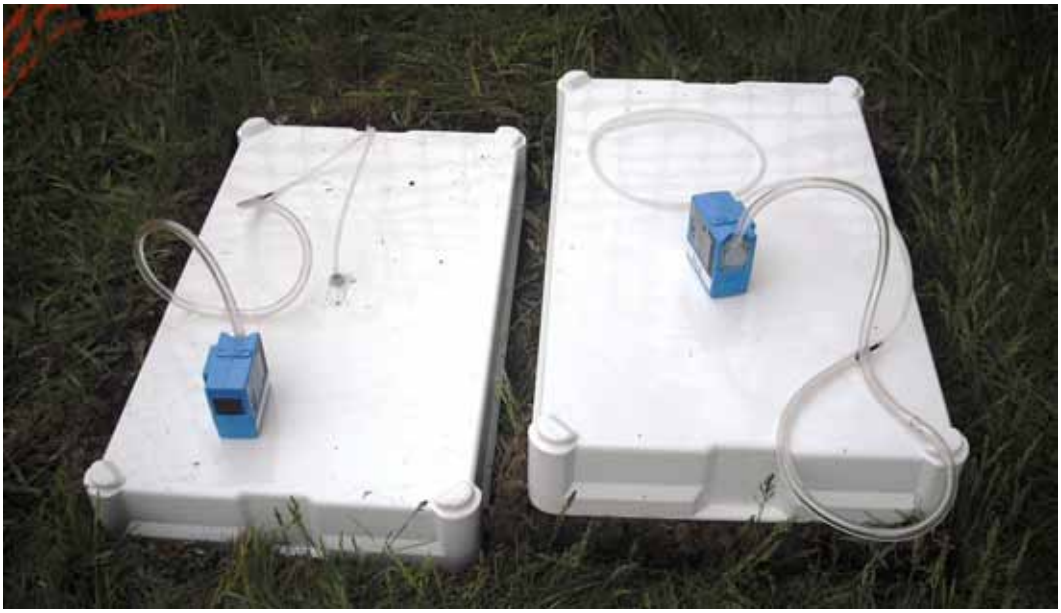

Figure 7. Surface air sampling.

A 2-ft-deep borehole in the soil was created (Figure 8) with a 2-in.-diameter hand coring device to obtain the core samples. The original goal was to achieve a 36-in.-deep hole; however, refusal was reached at approximately 24 in. below-ground-surface (bgs) depth due to concrete

debris encountered at that depth. Samples were removed from the cores to give a depth profile of pesticide concentrations at 2 to 8, 8 to 16, and 16 to 24 inches bgs. Each section of the core for the corresponding depths was homogenized by hand in the laboratory and sampled for analysis. Air sampling from the borehole was accomplished by placing the sorbent tube near the bottom of the borehole. The sorbent tube was attached to PVC tubing, which was connected to the sample pump at the surface. To simulate the conditions of an open trench on a construction site, the borehole was not capped at any time.

Figure 8. Borehole.

Analytical methods

Air samples were collected and analyzed according to NIOSH Method 5510 (NIOSH 2003). Air samples were drawn through the Chromosorb 102 sorbent tubes at a constant rate of 1L/min utilizing a Synsidyne GilAir-3 air sampling pump. Air samples were collected for a total of 2 hr for a total sample volume of 120 L. Field and media blanks were not used due to the low risk of volatile chlordane contamination from the environment. Samples were packaged inside a cooler with bubble wrap and shipped by overnight delivery for analysis by Argus Analytical located in Ridgeland, Mississippi.

Soil samples were removed from the collection cylinders and placed in 2-ounce amber jars. The sample jars were packaged in a cooler and shipped by overnight delivery for analysis by Argus Analytical. Soil samples were analyzed by EPA Method SW846 8081A (USEPA 1999a).

Results

Results from air samples taken are provided in Table 7. All air sample results from the field study were non-detect except for the initial sample taken from the borehole. The concentration reported for this sample was 11.7 µg/m³. The day 1 shallow disturbance sample was destroyed during the shipping process from Ft. Dix to ERDC. No control samples were taken for days 7 and 63.

Table 7. Ft. Dix air concentrations from soil.

Sample	Day 1	Day 7	Day 63
	Chlordane Concentration (µg/m³)		
Control	< 8.3	N/S	N/S
Root-zone	< 8.3	< 8.3	< 8.3
Denuded Soil	< 8.3	< 8.3	< 8.3
Shallow Disturbance	N/S*	< 8.3	< 8.3
Borehole	11.7	< 8.3	< 8.3

<: non detect, number provided is detection limit

N/S: no sample

* sample broken during shipment

Even though the sorbent sample taken from the borehole was the only sample that produced any detectable levels of chlordane, there was chlordane present in each layer of the soil tested. The results of soil analyses for chlordane are given in Table 8 and depicted in Figure 9. Soil concentration levels increased as the depth of the soil increased. The lowest concentration was seen in the sample from the root zone area, which was approximately 1 to 2 in. bgs and the top 4 in. of the core sample. The highest concentrations were seen in samples of the soil core taken from 12 to 24 in. bgs.

Discussion

The depth profile of chlordane concentrations in the soil at the test site suggest that it was likely applied in a trench excavated to a depth of approximately 1 ft, which is consistent with historical knowledge of the site. The lower concentrations at shallower depths are likely due to the process of chlordane volatilization from treated soil and re-adsorption to less contaminated soil as it moved upward in the vadose zone.

Table 8. Ft. Dix soil chlordane results.

Sample (Ft. Dix Soils)	Mean (mg/Kg)	Std Dev.
Root-zone	0.14	0.10
Denuded soil	0.38	0.42
Shallow disturbance	21.87	12.87
Core Sample @ 0-4”	0.09	NA
Core Sample @ 4-8”	0.92	NA
Core Sample @ 8-12”	2.63	NA
Core Sample @ 12-16”	20.60	NA
Core Sample @ 16-20”	20.70	NA
Core Sample @ 20-24”	21.3	NA

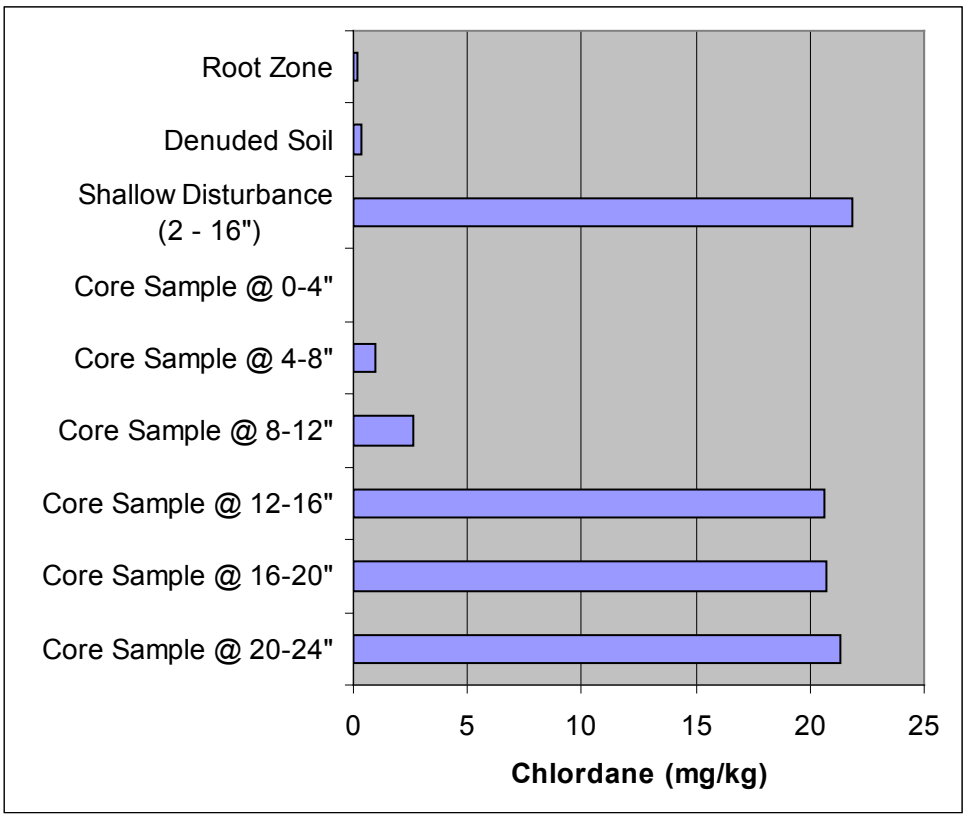

Figure 9. Ft. Dix soil chlordane profile.

Collection of gas samples provided only one positive result. This sample was collected from the bottom of the bore hole immediately after excavation and was determined to be 11.7-µg/m^3, which is far below the recommended time weighted average (TWA) exposure limit of 0.5-mg/m^3 for workers exposed to chlordane. The sample collected from the same location the next day

indicated that the air concentration was below the detection limit of 8.3 μg/m^3. This suggests that even the most heavily contaminated soil from this site is unlikely to produce air conditions considered unsafe for workers by OSHA or NIOSH under the worst conditions likely to be encountered, which would be an open trench immediately after excavation.

4 Field Test at Mountain Home Air Force Base

The purpose of the sampling effort at Mountain Home Air Force Base (MHAFB), Idaho was to collect air samples from inside residences and sub-slab air and soil samples from directly beneath the foundation of the residences for chlordane analysis. The objective of these field experiments was to establish whether measurable quantities of chlordane vapor are currently present in the soil and whether these vapors pose any risk of vapor intrusion to the current structures or future structures built on these locations.

Chlordane is listed by the U.S. Department of Defense (DoD) as being sufficiently toxic and volatile to potentially pose a significant risk of soil vapor intrusion into inhabited buildings (DoD 2009) due to transport pathways such as advection, convection, and diffusion. These mechanisms are generally most active beneath or directly adjacent to buildings where there can be a negative pressure differential between the building and the surrounding soil that tends to pull soil gas upwards towards the building.

Mr. Scott Waisner of the U.S. Army Engineer Research and Development Center (ERDC) and Mr. Michael Jones of Applied Research Associates (ARA) were responsible for project setup, sample collection, and sample preparation for analysis. Mrs. Tammy Phillips (208-828-8003) of the MHAFB Civil Engineering Environmental Office (CEAN) coordinated and assisted with site access. Sampling was conducted at MHAFB from 5-9 October 2009.

Materials and methods

Test sites

The areas chosen by CEAN and ERDC for sampling were eight former housing units for military families. Four types of dwellings were studied: single-level duplexes, two-level 8-unit dwellings, two-level 12-unit dwellings, and single-level 6-unit dwellings. Two units of each dwelling type were tested. Aerial photos of the two subdivisions with the various structures studied are provided in Appendix C. Due to the invasive nature of the sampling efforts, all units selected were not currently occupied and

either currently scheduled for demolition or no habitation is planned prior to being demolished. The types of units selected are representative of common designs for military housing units at or nearing the end of their planned useful life.

The duplexes were located at 4432B (N43° 3'10" W115°51'2") and 4433B (N43° 3'10" W115°51'6") Sijan Street in the Gunfighter Manor subdivision (Appendix C). Unit 4432B is shown in Figure 10. Each duplex unit had a foundation footprint of approximately 1500 ft², and the floor plans were identical for the two units tested. The floor plan is depicted in Figure 11 with the indoor air and sub-slab sample locations indicated. There were eight sub-slab sample locations and one indoor air sample location in each of the duplex units tested.

Figure 10. One of the duplex housing units tested in this study, 4432B Sijan Street.

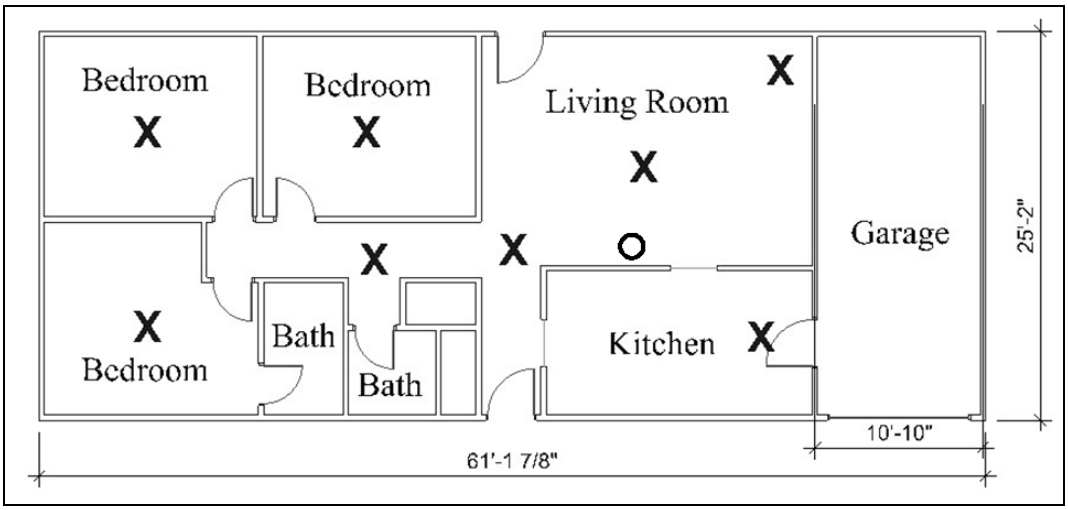

Figure 11. Floor plan for 4433B Sijan Street. Sub-slab testing locations are indicated by an "X," and indoor vapor sample location is indicated by an "O."

The remaining units chosen for sampling were multi-unit dwellings in the Dunes subdivision located on Mellen Drive, now named Chestnut Street (Appendix C). Units 4816 E and F (N43° 3'46" W115°51'7") were two adjacent units in an 8-unit building, which is shown in Figure 12. Each two-story unit had a foundation footprint of approximately 600 ft^2, and the floor plans for units E and F are mirror images of each other. The floor plan for unit E is depicted in Figure 13 with the sub-slab and indoor-air sample locations indicated. Because of the small foundation footprint of these units, four sub-slab sample locations were used in each of the adjacent units, and one indoor air sample was collected from unit E.

Figure 12. One of the eight-unit dwellings studied, 4816 Mellen Drive.

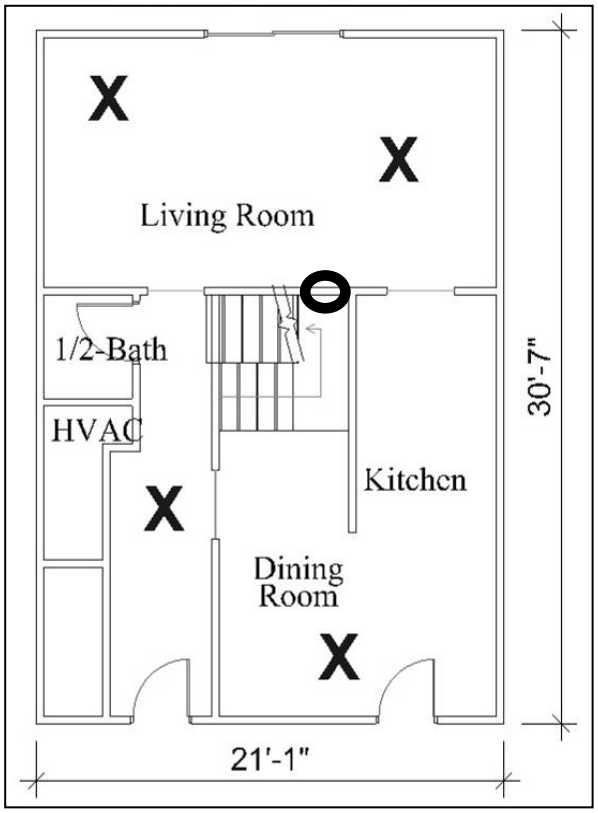

Figure 13. Floor plan for 4816E Mellen Dr. Sub-slab testing locations are indicated by an "X," and indoor vapor sample location is indicated by an "O."

Units 4818L and M (N43° 3'43" W115°51'5") were two adjacent units in a 12-unit building, and are shown in Figure 14. Each two-story unit had a foundation footprint of approximately 600 ft^2, and the floor plans for units L and M are mirror images of each other. The floor plan for unit M is depicted in Figure 15 with the sub-slab and indoor-air sample locations indicated. Because of the small foundation footprint of these units, four sub-slab sample locations were used in each of the adjacent units, and one indoor air sample was collected from unit M.

Units 4824 D and E (N43° 3'44" W115°51'2") were part of a 6-unit building located in the Dunes and are shown in Figure 16. Each single-story unit had a foundation footprint of approximately 1080 ft^2, and the floor plans for units D and E are mirror images of each other. The floor plan for unit D is depicted in Figure 17 with the sub-slab and indoor-air sample locations indicated. Four sub-slab sample locations were used in each of the adjacent units, and one indoor air sample was collected from unit E.

Air sampling

Two different types of air samples were taken, indoor and sub-slab. All air samples were collected by drawing air through Chromosorb-102 sorbent tubes at a constant flow rate using one of the following models of Sensidyne air-sampling pumps: GilAir-3, GilAir-5, or BDX II. Several models were used to provide a sufficient number of sampling pumps to conduct the sampling effort in a timely manner. All pumps were calibrated to a flow rate of 1 L/min prior to use in this study.

Figure 14. One of the 12-unit dwellings studied, 4818 Mellen Drive.

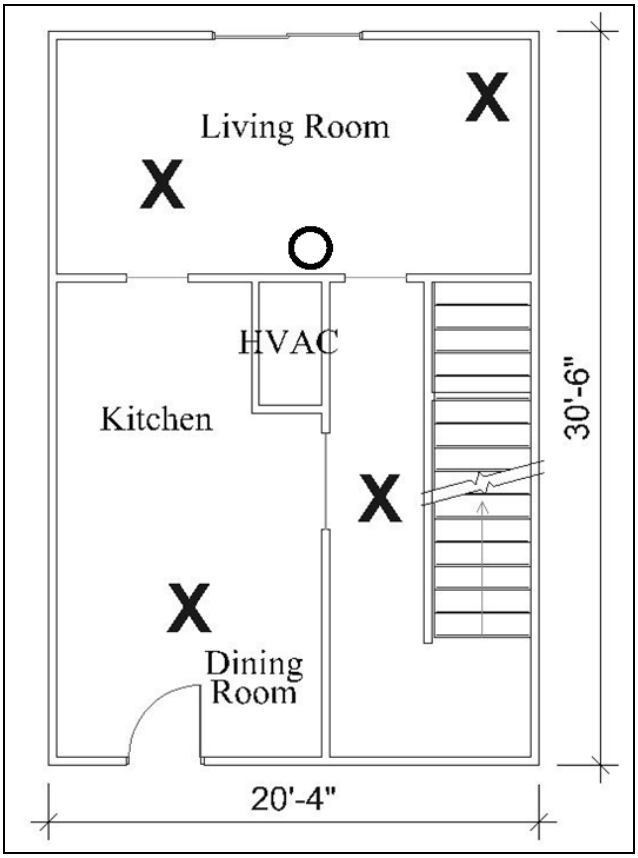

Figure 15. Floor plan for 4818M Mellen Drive. Sub-slab testing locations are indicated by an "X," and indoor vapor sample location is indicated by an "O."

Figure 16. One of the six-unit structures studied, 4824 Mellen Drive.

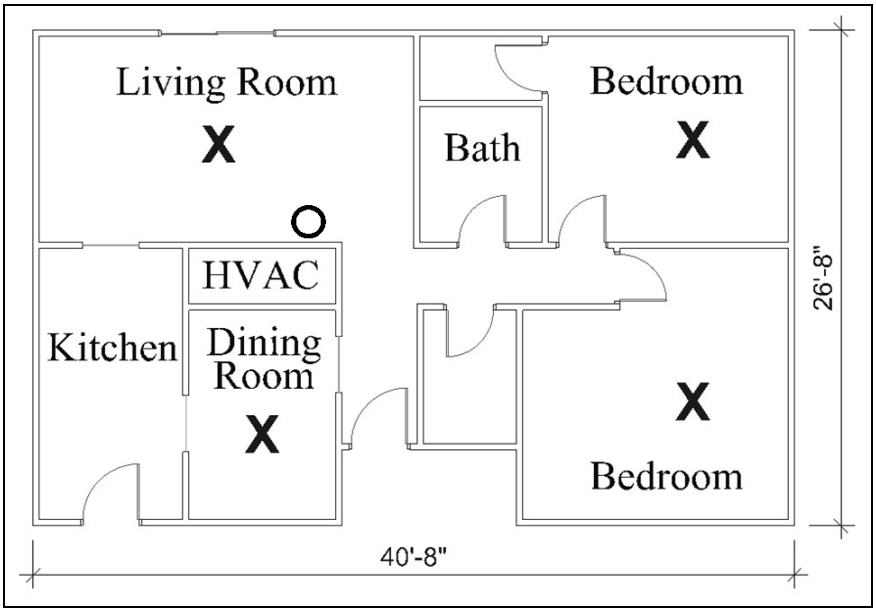

Figure 17. Floor plan for 4824D Mellen Drive. Sub-slab testing locations are indicated by an "X," and indoor vapor sample location is indicated by an "O."

Indoor air sampling. Indoor air samples were collected prior to drilling any holes through the foundations of the units. Indoor air samples were taken from each of five separate units: 4432B and 4433B Sijan Street and 4816E, 4818L, and 4824E Mellen Drive. A centralized location was selected in each of these units, since only one air sample was being collected per unit. Samples were collected by drawing the air through sorbent tubes at a constant flow rate of 1 L/min for a period of 24 hr. This volume of sample produced a sample detection limit of 0.4 μg/m^3, which is below the 10^{-4} cancer risk level of 0.7 μg/m^3. This risk level was chosen to match that used for the sub-slab gas sampling effort described below.

Sub-slab air sampling. Peninsula Sawing & Drilling (208-587-9071) of Mountain Home, Idaho was contracted to drill 1-in. holes through the foundation slabs (Figure 18). Prior to drilling or cutting, floor covering such as carpet, tiles, and parquet flooring was removed.

Sub-slab air samples were taken from each of the eight separate units. In order to increase the likelihood of a positive result, an attempt was made to distribute the sample locations over the footprint of the tested units. Access to the sub-slab was created by drilling 1-in.-diam holes through the foundation slab at each sample location. A section of 5/8-in. PVC tubing was placed into each hole, and an airtight seal between the tube and the wall of the drilled hole was formed with expanding polyurethane foam.

The sorbent tube was then connected to the tubing and an air sampling pump (Figure 19). Samples were collected by drawing the air through a sorbent tube at a constant flow rate of 1 L/min for a period of 4 hr.

Figure 18. Drilling 1-in. holes.

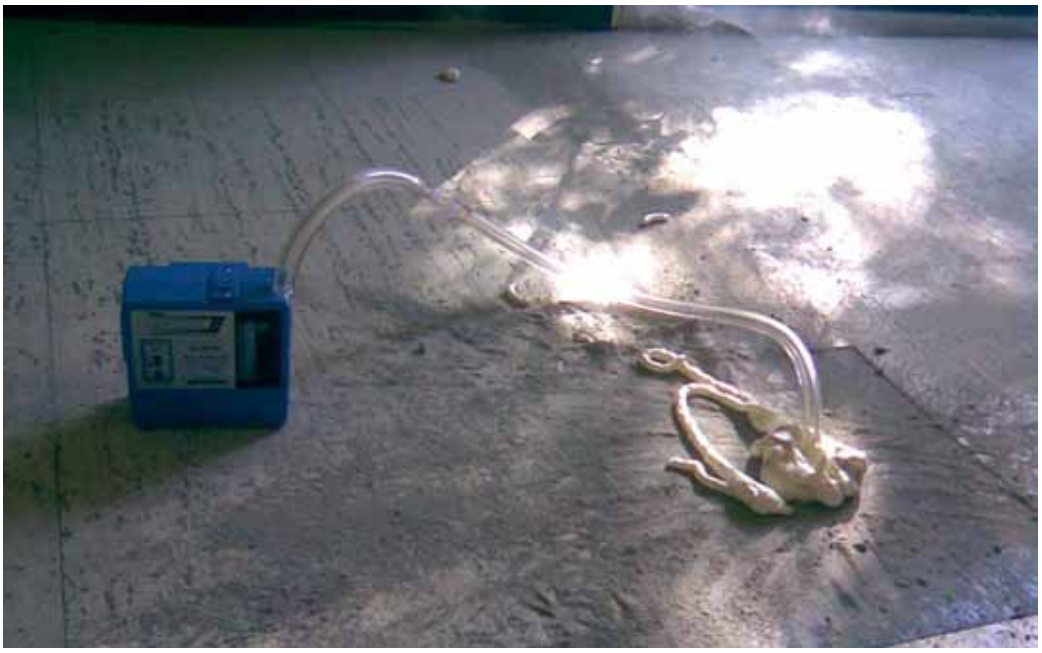

Figure 19. Sub-slab air sampling.

Sampling volumes. The decision to limit the sub-slab sample volumes to 240 L was based on several factors and assumptions including the volume of gas immediately under the slab and anticipated soil-gas concentrations. To reach a 10^{-6} cancer risk target detection level (0.24 μg/m^3) in sub-slab soil gas would have required a gas sample volume of 4167 L. This target sub-slab concentration is based on an attenuation factor of 0.1 between the sub-slab gas concentration and the indoor air concentration that is equivalent to the 10^{-6} cancer risk level, 0.024 μg/m^3. Collection of a sample of this volume would require drawing a sample for 2.9 days at a rate of 1 L/min. Assuming 3 in. of gravel under the foundation with an average porosity of 25%, the required sample volume would pull all the air under 2356 ft^2 of slab. Since the areas of the sampled slabs tested are estimated at either 1500, 600, or 1040 ft^2, this sample volume approaches or exceeds the volume of soil gas likely in the gravel layer under the slabs. Complicating this issue further was the requirement to collect samples from multiple locations under each slab. Further, based on soil gas concentrations of chlordane predicted by the Johnson and Ettinger (1991) model and soil gas concentrations found at Fort Dix, New Jersey, it is possible to saturate the sorbent columns if the air sample drawn is too large, and a 240-L gas sample was considered likely to be sufficient to exceed the detection limit. For these reasons, it was decided to choose sample volumes sufficient to produce a detection limit of 4.2 μg/m^3, which is below the 10^{-5} cancer risk level for shallow soil gas (7.0 μg/m^3).

Sub-slab soil sampling

Following completion of air sampling in each unit, 6-in. diameter holes were cut through the foundation by Peninsula Sawing & Drilling at the same sample locations where the 1-in. holes were previously drilled (Figure 20). After the 6-in. concrete core was removed from each hole, the remaining gravel was removed by hand to access the underlying soil. The depth of gravel under the slabs ranged from 3 to 6 in. and consisted of river rock and pea gravel. A 12-in.-long soil core was collected into 2- butyrate plastic liners using a hand coring device. After coring was complete, the tubes of soil were capped and labeled for shipment back to ERDC.

All drilling and cutting proceeded without incident, except in unit 4432B Sijan Street. The 6-in. hole cut into the corner of the living room penetrated the underground HVAC duct. A second hole was cut and again encountered a ventilation duct. The third hole that was cut missed the duct and was used to collect the soil sample.

Figure 20. Cutting 6-in. holes.

Analytical methods

Chromosorb-102 sorbent tubes used to collect air samples were shipped to Argus Analytical, Inc. located in Ridgeland, Mississippi (601-957-2676). Sorbent tubes were extracted and analyzed for chlordane according to NIOSH Method 5510 (NIOSH 2003). Due to the low volatility and recalcitrant nature of the chemical of interest and the stated goals of this study, it was deemed unnecessary to pack the samples on ice for shipment to the analytical laboratory.

Following receipt of soil cores at ERDC, soil cores were cut in half to produce an upper and lower 6-in. soil sample. Soils from each half of the soil cores were then homogenized separately. A representative sample of each half of the soil core was then packed in a glass sample jar. This process created a total of 80 soil samples, which were then shipped to Argus Analytical to be analyzed for pesticides. Extraction and analysis of soil samples was carried out according to EPA SW-846 (USEPA 1999a) Methods 3545A and 8081A, respectively. Due to logistical constraints, some soil samples were not extracted until 16 days following collection, which exceeded the 14-day holding limit listed in SW-846 for these analytes.

Results

The results for all samples were non-detect for chlordane or other related pesticides. The method reporting limits and associated risk limits are

provided in Table 9. The estimated sub-slab air concentrations provided for the associated risk levels in Table 9 are based on an attenuation factor of 0.1 ($C_{indoor}/C_{subslab}$) relative to the corresponding indoor air concentration. The estimated sub-slab soil concentration values for associated risk are based on default parameters for building, loam soil type, and exposure times from the SL-SCREEN Microsoft Excel based J&E model (EQM 2004) provided by the USEPA. The method reporting limits were below the estimated 10^{-4} risk levels for indoor and sub-slab air concentrations and below the estimated 10^{-6} risk level for sub-slab soil concentrations.

Table 9. Method reporting and risk limits.

Sample Type	Method Reporting	10^{-6} Risk carcinogen	10^{-4} Risk non-carcinogen
Indoor Air (µg/m³)	0.69	0.024	0.7
Sub-slab Air (µg/m³)	4.2	0.24†	7.0†
Sub-slab Soil (mg/kg)	0.200	3.61‡	108‡

† These values are based on an attenuation factor of 0.1 from the associated indoor air risk limits.

‡ These values are based on the J&E model SL-SCREEN spreadsheet using default parameters for buildings, loam soil, exposure times.

It is not known whether the lack of chlordane detection was the result of this pesticide never being applied below the slabs or loss of the pesticide over the five decades since application.

Discussion

Sub-slab gas sampling for chlordane was complicated by the large volume of soil gas necessary to reach method detection limits equivalent to the 10^{-6} cancer risk level with an attenuation factor of 0.1 between sub-slab gas and indoor air. The appropriate low-flow methods for detection of chlordane in ambient air are NIOSH Method 5510 (NIOSH 2003) and EPA Method TO-10A (USEPA 1999b). Both methods have similar detection limits of 1 µg per sample. Given that this method detection limit requires a sample volume equivalent to the air under approximately 2400 ft² of slab, serious consideration needs to be given by the regulatory community as to how sub-slab sampling for this compound should be conducted. Collection of sufficient sample volume to reach the detection limit goals from multiple samples and possibly even a single sample location can result in pulling air from outside the footprint of the slab. This problem is likely to occur for sub-slab sampling of other compounds with high molecular weight and/or low volatility. Development of a passive gas-sampling method for these compounds is recommended.

5 Conclusions and Recommendations

Results from laboratory tests indicated that the specific mass-transfer rates of chlordane from aged soil are low and are positively correlated with relative humidity levels and the temperature of the soil. Detection of chlordane in the air was only accomplished at the elevated temperature of 50°C, which is unlikely to occur in soils. Soil type and contamination levels also appear to influence the rate of volatilization. The specific mass-transfer rates measured in these tests ranged from 0.82-3.81 µg/kg/day.

Field tests conducted at Ft. Dix suggest that construction activities may release measurable levels of chlordane from legacy treatment, but that these levels will be well below the OSHA and NIOSH recommended time-weighted average of 0.5 mg/m^3. The concentration of chlordane near the soil will drop rapidly after disturbance of the soil.

Field tests conducted at MHAFB did not produce any detectable levels of chlordane in either the sub-slab soil and air samples or the indoor air samples. Therefore, no conclusions could be drawn regarding vapor intrusion of chlordane applied below slab foundations from these tests.

Based on previous reports, contamination of indoor air by chlordane occurs primarily when post-construction sub-slab injection of chlordane is conducted in housing units with ducts in or below the slab. This situation runs a high risk of chlordane emulsion leaking directly into the ventilation ducts and contaminating the indoor air shortly after injection. Treatment of soils below the foundation prior to pouring the slab appears to run a very low risk of contaminating indoor air with chlordane. Based on the observation of these historical surveys, it is very unlikely that construction of new housing units on areas historically treated with chlordane will pose a risk of vapor intrusion by chlordane.

The laboratory study focused on the effect of environmental parameters (disturbance, temperature, RH, etc.) on the flux of volatile chlordane. This scope did not address the parameters of the soil itself that could result in flux differences from some soils compared to others. Table 6 indicated that a volatilization of chlordane was measured out of Davis-Monthan soil at 20 °C and at 50% RH. No chlordane volatility was observed for the other

soils tested at this condition (McGuire and WES aged). The Davis-Monthan soil had two clear differences compared to the other soils that might have resulted in it having a measurable flux. First, it had a substantially higher chlordane concentration (>13,000 μg kg^{-1} vs. 2,683 μg kg^{-1} for the McGuire and 21.3 μg kg^{-1} for the aged-spiked WES). Second, it had a lower TOC concentration than the other soils. Organic carbon commonly complexes with organic contaminants like chlordane, making them more strongly sorbed. Either of these two factors could have resulted in the enhanced chlordane flux from the Davis-Monthan soil. However, there may also be other factors that could also have affected the result. These include intraparticle soil porosity, differences in contaminant weathering (e.g. Davis-Monthan is from a dry desert area compared to the more temperate climate of McGuire AFB), and even possible differences in mineralogy.

A possible follow-on study could address the effect of soil parameters on chlordane volatility. This could more thoroughly investigate parameters like organic content, particle porosity, chlordane concentration, and soil mineralogy, all of which could be easily measured and applied to models. Further studies could address differences in weathering, although quantifying this for a model would be much more difficult.

The Johnson and Ettinger model does not appear to take into account the limit that sorption forces between contaminants and soil may place on the volatilization rate of contaminants. While this phenomenon may not be very significant when dealing with volatile compounds such as chlorinated solvents, it may have very significant limitations on the specific mass-transfer rates necessary to sustain vapor intrusion by high molecular weight compounds such as chlordane that bind tightly to soil particles. Depending on the estimated extent of the problem caused by compounds such as chlordane that are on the vapor intrusion list, it may be in the DoD's best interest to conduct work to establish models to predict flux rates from aged soils and to modify the current vapor intrusion model to take these limited flux rates into account.

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Appendix A: Laboratory Test Data

Sample ID:	M-22-10-N		*McGuire AFB Soil, T=22°C, RH=10%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
2/18/2009 0900	0.00	50	0									
2/19/2009 0900	1.00	50	72	1.00	ND	ND	ND	13.89	ND	< 1	< 20	< 219.3
2/23/2009 0900	5.00	50	288	1.00	ND	ND	ND	3.47	ND	< 0.25	< 5	< 54.8
3/6/2009 0900	16.00	50	792	1.00	ND	ND	ND	1.26	ND	< 0.09	< 1.82	< 19.9
3/23/2009 0900	33.00	50	1224	1.00	ND	ND	ND	0.82	ND	< 0.06	< 1.18	< 12.9
5/20/2009 0900	91.00	50	4176	1.00	ND	ND	ND	0.24	ND	< 0.02	< 0.34	< 3.8
Sample ID:	M-22-50-N		*McGuire AFB Soil, T=22°C, RH=50%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
2/18/2009 0900	0.00	50	0									
2/19/2009 0900	1.00	50	72	1.00	ND	ND	ND	13.89	ND	< 1	< 20	< 219.3
2/23/2009 0900	5.00	50	288	1.00	ND	ND	ND	3.47	ND	< 0.25	< 5	< 54.8
3/6/2009 0900	16.00	50	792	1.00	ND	ND	ND	1.26	ND	< 0.09	< 1.82	< 19.9
3/23/2009 0900	33.00	50	1224	1.00	ND	ND	ND	0.82	ND	< 0.06	< 1.18	< 12.9
5/20/2009 0900	91.00	50	4176	1.00	ND	ND	ND	0.24	ND	< 0.02	< 0.34	< 3.8
Sample ID:	M-22-90-N		*McGuire AFB Soil, T=22°C, RH=90%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
2/18/2009 0900	0.00	50	0									
2/19/2009 0900	1.00	50	72	1.00	ND	ND	ND	13.89	ND	< 1	< 20	< 219.3
2/23/2009 0900	5.00	50	288	1.00	ND	ND	ND	3.47	ND	< 0.25	< 5	< 54.8
3/6/2009 0900	16.00	50	792	1.00	ND	ND	ND	1.26	ND	< 0.09	< 1.82	< 19.9
3/23/2009 0900	33.00	50	1224	1.00	1.10	ND	ND	0.82	0.90	0.06	1.29	14.19
5/20/2009 0900	91.00	50	4176	1.00	2.18	ND	ND	0.24	0.52	0.04	0.75	8.24

Sample ID:	M-10-50-N		*McGuire AFB Soil, T=10°C, RH=50%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
6/2/2009 1100	0.00	50	0									
6/3/2009 1100	1.00	50	72	1.00	ND	ND	ND	13.89	ND	< 1	< 20	< 219.3
6/5/2009 1100	3.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 109.6
6/12/2009 1100	10.00	50	504	1.00	ND	ND	ND	1.98	ND	< 0.14	< 2.86	< 31.3
7/2/2009 1100	30.00	50	1440	1.00	ND	ND	ND	0.69	ND	< 0.05	< 1	< 11
8/31/2009 1100	90.00	50	4320	1.00	ND	ND	ND	0.23	ND	< 0.02	< 0.33	< 3.7
Sample ID:	M-40-50-N		*McGuire AFB Soil, T=40°C, RH=50%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
2/27/2009 0900	0.00	50	0									
3/2/2009 0900	3.00	50	216	1.00	ND	ND	ND	4.63	ND	< 0.33	< 6.67	< 73.1
3/4/2009 0900	5.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 109.6
3/9/2009 0900	10.00	50	360	1.00	ND	ND	ND	2.78	ND	< 0.2	< 4	< 43.9
3/30/2009 0900	31.00	50	1512	1.00	ND	ND	ND	0.66	ND	< 0.05	< 0.95	< 10.4
5/28/2009 0900	90.00	50	4248	1.00	ND	ND	ND	0.24	ND	< 0.02	< 0.34	< 3.7
Sample ID:	M-50-50-N		*McGuire AFB Soil, T=50°C, RH=50%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
6/2/2009 1100	0.00	50	0									
6/3/2009 1100	1.00	50	72	1.00	ND	ND	ND	13.89	ND	< 1	< 20	< 219.3
6/5/2009 11:00	3.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 109.6
6/12/2009 1100	10.00	50	504	1.00	ND	ND	ND	1.98	ND	< 0.14	< 2.86	< 31.3
7/2/2009 1100	30.00	50	1440	1.00	ND	ND	ND	0.69	ND	< 0.05	< 1	< 11
8/31/2009 1100	90.00	50	4320	1.00	2.45	ND	ND	0.23	0.57	0.04	0.82	8.95

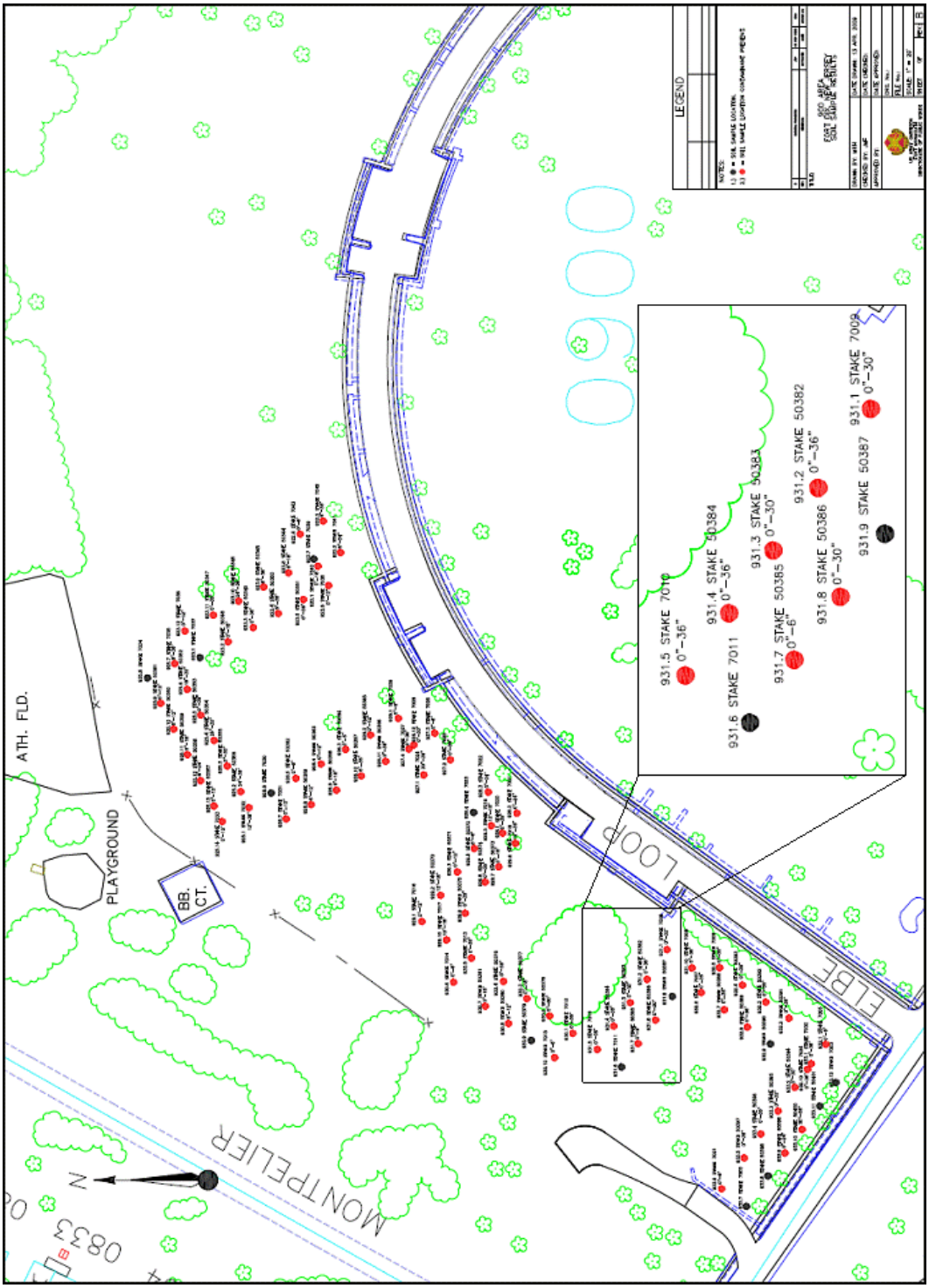
Sample ID:	M-22-50-W		*McGuire AFB Soil, T=22°C, RH=50%, weekly disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
2/27/2009 0900	0.00	50	0									
3/2/2009 9:00	3.00	50	216	1.00	ND	ND	ND	4.63	ND	< 0.33	< 6.67	< 73.1
3/4/2009 0900	5.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 109.6
3/9/2009 0900	10.00	50	360	1.00	ND	ND	ND	2.78	ND	< 0.2	< 4	< 43.9
3/30/2009 0900	31.00	50	1512	1.00	ND	ND	ND	0.66	ND	< 0.05	< 0.95	< 10.4
5/28/2009 0900	90.00	50	4248	1.00	ND	ND	ND	0.24	ND	< 0.02	< 0.34	< 3.7
Sample ID:	M-22-50-D		*McGuire AFB Soil, T=22°C, RH=50%, daily disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
2/27/2009 0900	0.00	50	0									
3/2/2009 9:00	3.00	50	216	1.00	ND	ND	ND	4.63	ND	< 0.33	< 6.67	< 73.1
3/4/2009 0900	5.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 109.6
3/9/2009 0900	10.00	50	360	1.00	ND	ND	ND	2.78	ND	< 0.2	< 4	< 43.9
3/30/2009 0900	31.00	50	1512	1.00	ND	ND	ND	0.66	ND	< 0.05	< 0.95	< 10.4
5/28/2009 0900	90.00	50	4248	1.00	ND	ND	ND	0.24	ND	< 0.02	< 0.34	< 3.7
Sample ID:	D-22-50-N		*Davis-Monthan AFB Soil, T=22°C, RH=50%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
2/27/2009 0900	0.00	50	0									
3/2/2009 9:00	3.00	50	216	1.00	ND	ND	ND	4.63	ND	< 0.33	< 6.67	< 73.1
3/4/2009 0900	5.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 109.6
3/9/2009 0900	10.00	50	360	1.00	ND	ND	ND	2.78	ND	< 0.2	< 4	< 43.9
3/30/2009 0900	31.00	50	1512	1.00	4.00	ND	ND	0.66	2.65	0.19	3.81	41.77
5/28/2009 0900	90.00	50	4248	1.00	1.02	ND	ND	0.24	0.24	0.02	0.35	3.79

Sample ID:	W-22-50-N		*WES Soil, T=22°C, RH=50%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
2/27/2009 0900	0.00	50	0									
3/2/2009 9:00	3.00	50	216	1.00	ND	ND	ND	4.63	ND	< 0.33	< 6.67	< 73.1
3/4/2009 0900	5.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 109.6
3/9/2009 0900	10.00	50	360	1.00	ND	ND	ND	2.78	ND	< 0.2	< 4	< 43.9
3/30/2009 0900	31.00	50	1512	1.00	ND	ND	ND	0.66	ND	< 0.05	< 0.95	< 10.4
5/28/2009 0900	90.00	50	4248	1.00	ND	ND	ND	0.24	ND	< 0.02	< 0.34	< 3.7
Sample ID:	Wa-22-50-N (Unspiked)		*WES Soil (aged), T=22°C, RH=50%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
6/2/2009 1100	0.00	50	0									
6/3/2009 1100	1.00	50	72	1.00	ND	ND	ND	13.89	ND	< 1	< 20	< 219.3
6/5/2009 11:00	3.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 109.6
6/12/2009 1100	10.00	50	504	1.00	ND	ND	ND	1.98	ND	< 0.14	< 2.86	< 31.3
7/2/2009 1100	30.00	50	1440	1.00	ND	ND	ND	0.69	ND	< 0.05	< 1	< 11
8/31/2009 1100	90.00	50	4320	1.00	ND	ND	ND	0.23	ND	< 0.02	< 0.33	< 3.7
Sample ID:	Wa-22-50-N (Spiked)		*WES Soil (spiked & aged), T=22°C, RH=50%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
6/2/2009 1100	0.00	50	0									
6/3/2009 1100	1.00	50	72	1.00	ND	ND	ND	13.89	ND	< 1	< 20	< 219.3
6/5/2009 11:00	3.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 109.6
6/12/2009 1100	10.00	50	504	1.00	ND	ND	ND	1.98	ND	< 0.14	< 2.86	< 31.3
7/2/2009 1100	30.00	50	1440	1.00	ND	ND	ND	0.69	ND	< 0.05	< 1	< 11
8/31/2009 1100	90.00	50	4320	1.00	ND	ND	ND	0.23	ND	< 0.02	< 0.33	< 3.7

Sample ID:	C-22-50-N		*McGuire AFB Clean Soil, T=22°C, RH=50%, no disturbance*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/kg/day)	Flux Rate (mg/m^2/day)
2/27/2009 0900	0.00	50	0									
3/2/2009 9:00	3.00	50	216	1.00	ND	ND	ND	4.63	ND	< 0.33	< 6.67	< 73
3/4/2009 0900	5.00	50	144	1.00	ND	ND	ND	6.94	ND	< 0.5	< 10	< 110
3/9/2009 0900	10.00	50	360	1.00	ND	ND	ND	2.78	ND	< 0.2	< 4	< 44
3/30/2009 0900	31.00	50	1512	1.00	ND	ND	ND	0.66	ND	< 0.05	< 0.95	< 10
5/28/2009 0900	90.00	50	4248	1.00	ND	ND	ND	0.24	ND	< 0.02	< 0.34	< 4

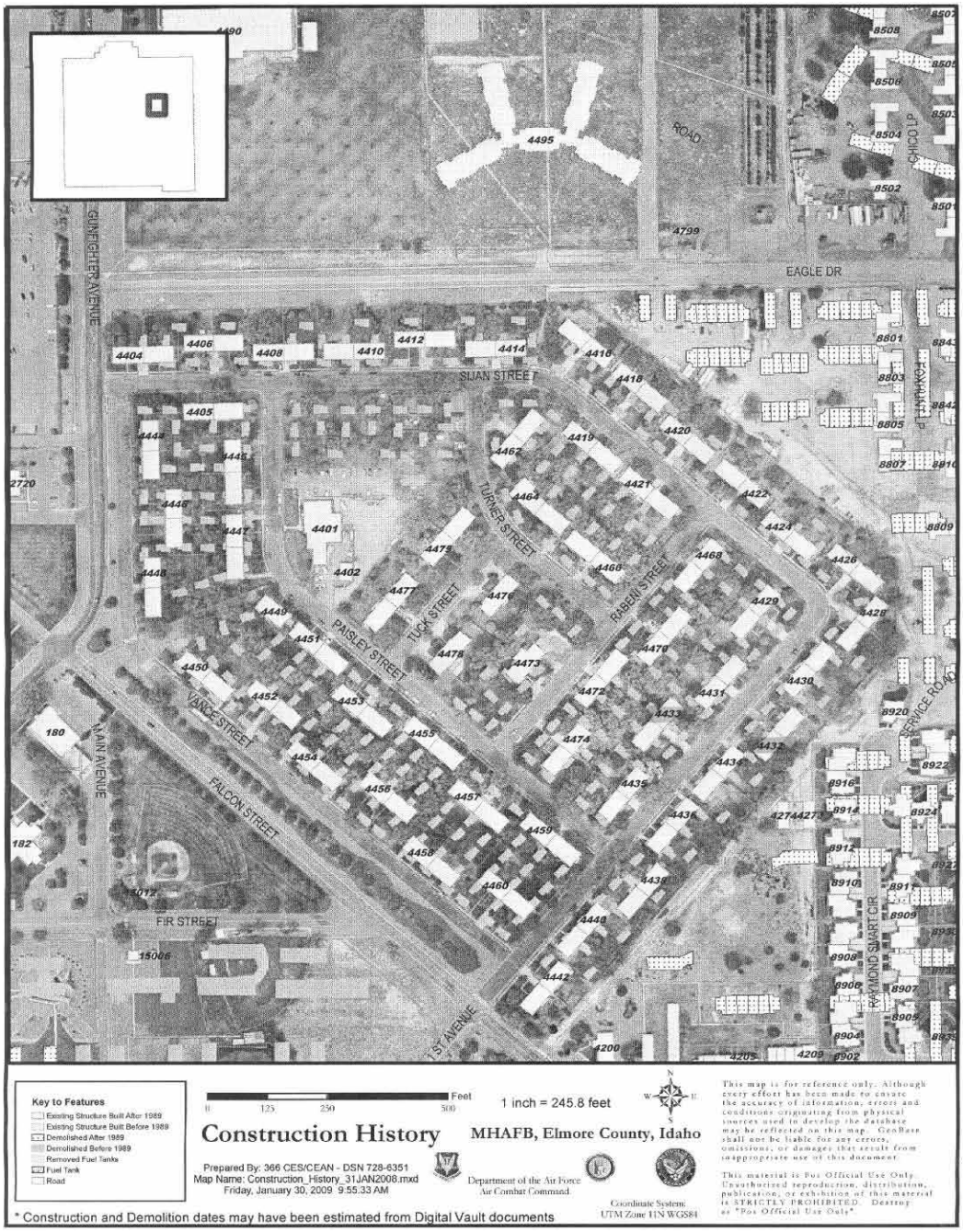
Sample ID:	Co-22-50-N		*Chlordane (technical) only, T=22°C, RH=50%, no disturbance (additional solution added at each sample event)*									
Date Time	ET (days)	Flow Rate (mL/min)	Sample Vol. (L)	Det. Limit (ug/tube)	Front (ug/tube)	Back (ug/tube)	Screen (ug/tube)	Det. Limit (ug/m^3)	Conc. (ug/m^3)	Flux Rate (ug/day)	Flux Rate (ug/L/day)	Flux Rate (mg/m^2/day)
6/29/2009 11:00	0.00	50	0	1.00								
6/30/2009 11:00	1.00	50	72	1.00	3.13	ND	ND	13.89	43.47	3.13	125	686
7/2/2009 11:00	3.00	50	144	1.00	6.45	ND	ND	6.94	44.79	3.23	129	707
7/9/2009 11:00	10.00	50	504	10.00	40.10	ND	1.30	19.84	82.14	5.91	237	1297
7/29/2009 11:00	30.00	50	1440	10.00	53.10	ND	ND	6.94	36.88	2.66	106	582
9/28/2009 11:00	91.00	50	4392	20.00	57.10	ND	ND	4.55	13.00	0.94	37	205

Appendix B: Ft. Dix Test Site Location

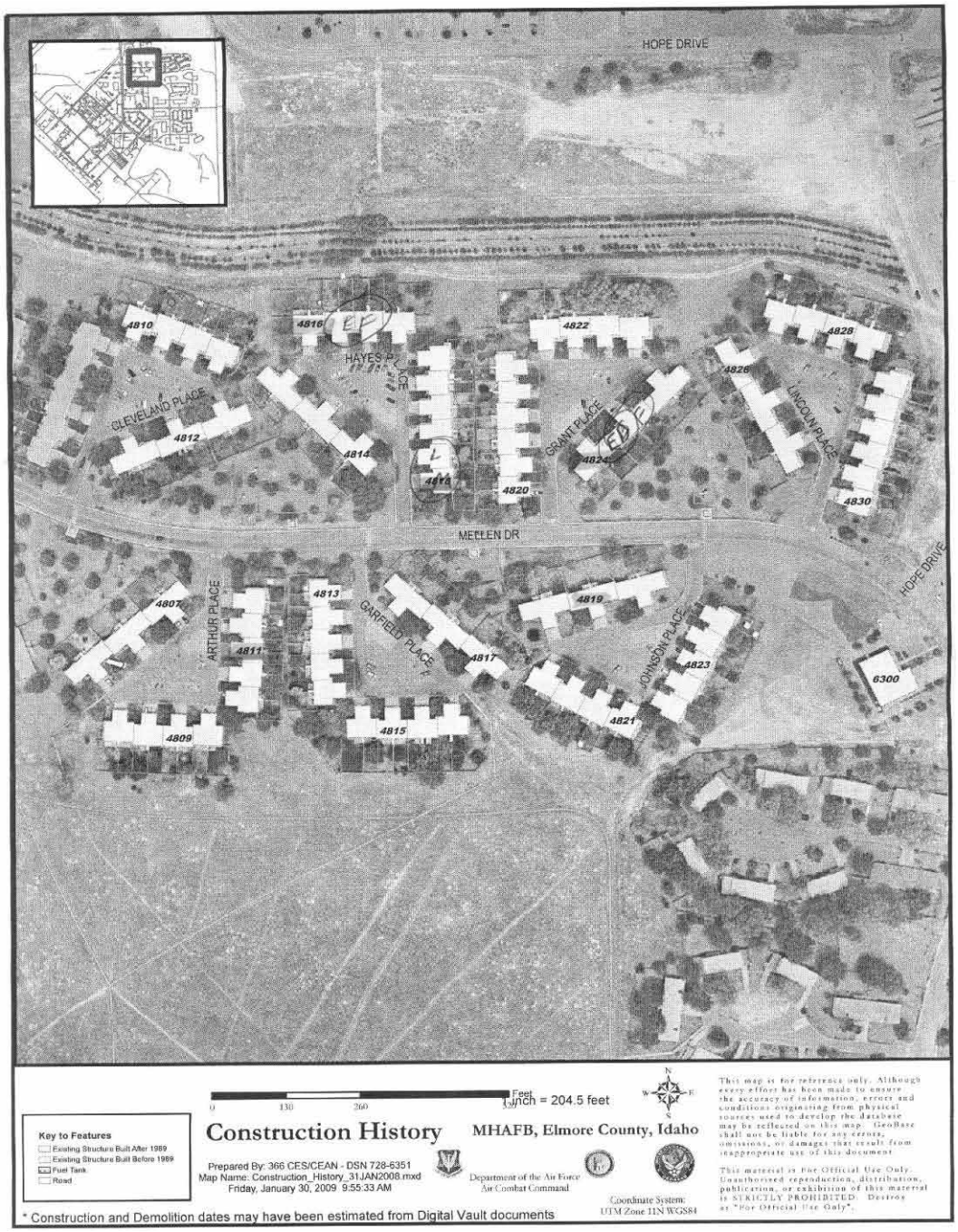


Appendix C: MHAFB Aerial Photos

Gunfighter Manor Subdivision



Dunes Subdivision



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14. ABSTRACT

The U.S. Air Force used the chlorinated pesticide chlordane to control termites around base housing until it was banned in 1988. As bases are closed, contracted, or realigned, soil issues associated with this pesticide must be addressed. One issue that is not well understood is chlordane volatility. There are documented cases where chlordane applied to soil resulted in vapor intrusion into buildings; however, all these cases involved freshly applied pesticides. The effect of aging and weather for at least 20 years would likely change the potential for volatilization of soil-applied chlordane.

This report covers three studies to assess volatility of aged chlordane in soil. The first was a laboratory study in a forced air system. Parameters such as temperature, relative humidity (RH), and various soil types were studied. Soils studied included chlordane-contaminated soils from McGuire Air Force Base (AFB), Davis-Monthan AFB, and a reference soil from the Vicksburg, MS, area called WES soil. Temperature variation studies (range from 10 to 50 °C) using soils from McGuire AFB at 50% RH found a measurable chlordane flux only at 50 °C. RH variation studies using McGuire AFB soil at 20 °C found a measureable flux only at the 90% RH level. Tests of the various soils at 20 °C and 50% RH indicated that of these, only the Davis-Monthan soil had a measurable chlordane flux.

(Continued)

15. SUBJECT TERMS
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Military bases
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14. ABSTRACT (concluded)

The second study was conducted in the field at Fort Dix Army Base to evaluate the effect of soil disturbance. This included simple vegetative removal, disturbance of the soil by tilling, and coring into the soil. Chlordane was found in all the sample locations and depths, with higher concentrations in deeper core samples. However, volatile chlordane was only detected in the borehole sample immediately after the hole was created.

The last study at Mountain Home AFB investigated volatility under slab foundations of housing at the base. Four housing types were tested. Indoor air sampling was conducted in each housing unit tested. This was followed by sampling of the sub-slab atmosphere by drilling holes through the foundation. Cores were then drilled through the foundation, and soil samples from below the slab were collected and analyzed for chlordane. No chlordane was found in the indoor air, sub-slab soil vapor, or the sub-slab soil samples at any of the housing units tested.