2

EDGEWOOD
RESEARCH,
DEVELOPMENT &
ENGINEERING
CENTER

ERDEC-CR-071

ENVIRONMENTAL AND HEALTH EFFECTS REVIEW FOR OBSCURANT FOG OIL

C.J. Driver
M.W. Ligotke
J.L. Downs
B.L. Tiller
T.M. Poston
E.B. Moore, Jr.
D.A. Cataldo

PACIFIC NORTHWEST LABORATORY
Richland, WA 99352

September 1993

Approved for public release; distribution is unlimited.

U.S. ARMY
CHEMICAL
AND BIOLOGICAL
DEFENSE AGENCY

Aberdeen Proving Ground, Maryland 21010-5423

Disclaimer

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1993 September

3. REPORT TYPE AND DATES COVERED
Final, 91 Jul - 93 Aug

4. TITLE AND SUBTITLE
Environmental and Health Effects Review for Obscurant Fog Oil

5. FUNDING NUMBERS
C-1FSL-2-4
PR-N4175692G012492

6. AUTHOR(S)
Driver, C.J.; Ligotke, M.W.; Downs, J.L.; Tiller, B.L.;
Poston, T.M.; Moore, E.B., Jr.; and Cataldo, D.A.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDEC-CR-071

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Joint Program Office, Naval Surface Warfare Center,
Dahlgren, VA 22448

DIR, ERDEC,* ATTN: SCBRD-RTL, APG, MD 21010-5423

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
COR: Randall S. Wentsel, SCBRD-RTL, (410) 671-2036

(Continued on page ii)

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The health and environmental effects of fog oil smoke were reviewed and compared to predicted levels of fog oil materiel in the field during typical testing and training scenarios. Fog oil dispersion and deposition for simulated mechanical vaporization/condensation releases were determined using a modified Gaussian atmospheric plume-dispersion model. Human health risks include respiratory discomfort and skin irritation; however, with appropriate respiratory and skin protection, SGF-2 poses no toxic threat to human health during typical test and training exposures. Fog oil is moderately harmful, either chemically or physically, to plants and animals and can accumulate in food chains. Waterfowl are particularly vulnerable to adverse physical and chemical effects of lubricating oils and experience reproductive dysfunction at relatively low levels of exposure. However, specific information on SGF-2 impacts on avian or mammalian wildlife is lacking. The volatile nature of fog oil suggests that any impacts would be rapidly attenuated in the environment. Also, the area of impact under typical testing and training scenarios would be small and no terrestrial population/community structure changes are anticipated from its use. Aquatic systems appear to be the most vulnerable to fog oil toxicity and SGF-2 deposition on aquatic systems should be avoided.

14. SUBJECT TERMS

Fog oil	Environmental effects	Human health	SGF-2
Wildlife	Terrestrial effects	Aquatic effects	

15. NUMBER OF PAGES
73

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

11. SUPPLEMENTARY NOTES (Continued)

*When this study was conducted, ERDEC was known as the U.S. Army Chemical Research, Development and Engineering Center, and the Contracting Officer's Representative was assigned to the Research Directorate.

EXECUTIVE SUMMARY

Fog oil smokes represent a fundamental capability needed to defeat visible detection and targeting. However, the human and environmental health risks of such releases must be evaluated for system development tests and simulated battle field training.

The purpose of this environmental review is to provide a technical basis to establish the health and environmental effects of fog oil smoke and to establish a basic resource for site-specific environmental assessments for training and test releases of fog oils. In addition, this review identifies important gaps in the data base and provides a framework for structuring research needs. To accomplish these goals, existing health and ecosystem effects data were evaluated and compared to predicted levels of fog oil materiel in the field. Because environmental data are limited for the fog oils used in military obscuration, environmental impacts of oil with similar chemical, physical, and toxicologic characteristics were also reviewed.

Fog oil dispersion and deposition for simulated mechanical vaporization/condensation releases were determined using a modified Gaussian atmospheric plume-dispersion model. Downrange air concentrations and surface mass loadings were estimated for single dissemination systems. Air concentrations and surface deposition decreased with downwind distance and with crosswind distance from the downwind vector at rates that were influenced by the atmospheric stability category. The most effective weathering processes on fog oil are dew formation, precipitation, evaporation, liquid-phase adhesion between deposited particles and surfaces, and microbial degradation.

Although the volatile nature of fog oils suggests that any impacts would be be rapidly attenuated in the environment, fog oils are toxic (chemically or physically) to a variety of aquatic organisms, plants, and wildlife species. Waterfowl are particularly vulnerable to adverse physical and chemical effects of lubricating oils and may experience reproductive dysfunction at relatively low levels of exposure. However, specific information on SGF-2 impacts on avian or mammalian wildlife is lacking. Fog oils can also accumulate in the food chain and provide a vehicle for uptake of fat-soluble xenobiotics. The potential area of deposition in which fog oil levels could cause harm in terrestrial systems is considered to be small, and population/community structure effects would not be detectable. However, aquatic systems appear more sensitive to fog oil deposition, and smoke contamination of water bodies should be avoided.

If only "new " fog oil stocks (i.e., stocks procured under MIL-F-12070C, Amendment 2 which require that fog oil be processed by severe hydrotreatment or refinement to eliminate polyaromatic hydrocarbons) are used and these stocks are tested prior to use to ensure that they are, indeed, carcinogen free, the human health effects appear to be minimal. However, additional information is needed to verify the relative sensitivity of laboratory models of fog oil health impacts and the outcome of chronic exposures experienced by some military personnel. Health risks with "new " fog oil include respiratory discomfort and skin irritation. These risks are easily minimized by attention to worker respiratory protection and personal hygiene. Reduced visibility on public roadways is a possibility at some testing sites and may increase the risk of vehicular accidents.

FOREWORD

Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Army.

X Where copyrighted material is quoted, permission has been obtained to use such material.

X Where material from documents designated for limited distribution is quoted, permission has been obtained to use the material.

X Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products of services of these organizations.

X In conducting research using animals, the investigators adhered to the "Guide for the Care and Use of Laboratory Animals" prepared by the Committee on Care and Use of Laboratory Animals of the Institute of laboratory Animal Resources, National Research Council (NIH Publication No. 86-23, revised 1985).

X For the protection of human subjects, the investigators have adhered to policies of applicable Federal law 45 CFR 46.

Crystal J. Driver 5/25/93

PI Signature Date

PREFACE

The work described in this report was authorized under Contract No. 1FSL-2-4 and Project No. N4175692G012492. This work was started in July 1991 and completed in August 1993.

The use of trade names or manufacturers' names in this report does not constitute an official endorsement of any commercial products. This report may not be cited for purposes of advertisement.

This report has been approved for release to the public. Registered users should request additional copies from the Defense Technical Information Center; unregistered users should direct such requests to the National Technical Information Service.

Blank

CONTENTS

Page

ENVIRONMENTAL AND HEALTH EFFECTS REVIEW FOR OBSCURANT FOG OIL

1. PURPOSE AND NEED

Modern warfare conditions and tactics require that land, sea, and air forces be trained with and have at their disposal a wide variety of offensive and defensive systems and materiels. Among these systems, smokes and obscurants have long been employed to mask movements of both troops and mechanized equipment. Smokes, which have been employed since the first world war, are widely used to visually mask the movements of both ground and sea forces. Vehicle exhaust systems and smudge pots are used to produce white obscurant smokes from liquid fog oil. A new generator (currently designated the XM56) enables the use of fog oil in combination with other materials, such as graphite flakes, and is an effort to improve the efficiency of smoke generation and to extend the effectiveness of the resulting obscurant cloud to include the infrared spectrum. Of the conventional smoke materials, fog oil is likely to remain heavily used because of its low cost, ease of handling and smoke generation, dispersion characteristics, and safety (Eberhard et al. 1989).

Because full-scale tests of prototype generation systems and multiple-generator training activities performed under actual field conditions are a necessary step in the process of development and implementation of fog oil as an obscurant smoke, human and environmental health impacts of fog oil generation must be assessed. The purpose of this study is to provide a technical review of the health and environmental effects of fog oil and to establish a basic resource for site-specific environmental assessments for training and test releases of fog oil smoke. In addition, important data gaps are identified to provide a framework for structuring research needs.

2. DESCRIPTION OF PROPOSED ACTION

This review of the use of fog oil aerosols includes consideration of their physical and chemical nature, dissemination, aerial transport, deposition, fate, and potential health and environmental impacts. Health concerns center on dermal and inhalation risk, and environmental concerns include potential terrestrial, aquatic, and wildlife impacts.

2.1 BACKGROUND

Fog oil smoke must be produced and disseminated in air to be effective as an electromagnetic obscurant in the visible spectrum. The efficacy of fog oil aerosols depends on air concentrations, temperature, fog oil droplet sizes, and other physical properties. In contrast to graphite flakes, which are mechanically disseminated, fog oil is disseminated by vaporization and then recondensation as the vapors cool in the atmosphere immediately beyond the exhaust pipe of the generation system. In the XM56 smoke generator, fog oil and graphite flake obscurants are released from the back of a single vehicle and mix in the air column downrange of the vehicle.

2.2 HISTORY

Fog oil is a middle distillate product of crude petroleum oil used in industry that has been adapted by the U.S. military for use in producing obscurant smoke screens.

2.2.1 Commercial Applications

Rather than being the result of specific processing for the military, fog oil is drawn from a lubricant stock sold as a raw material to various industries. Fog oil has been used as a diesel engine lubricating oil (Lushbaugh et al. 1950). Further refinement of lubricating oils similar to standard grade fuel No. 2 (SGF-2) may be performed to transform the pale oils to white oils. White oils are used for a variety of purposes that, depending on refining procedures, include metal working and cutting oils, newspaper ink (suspension of carbon black in white mineral oil), and agricultural pesticide and livestock sprays. Further refinement can produce medicinal mineral oil, which is used in various forms as a lubricant, laxative, and for other purposes (Liss-Suter and Villaume 1978)

2.2.2 Military Applications

Dense black smoke from incompletely burned crude oil was used to conceal U.S. Navy vessels during maneuvers in 1913 (U.S. Army 1986). Military uses of white fog oil obscurant smoke date from World War II and the Korean conflict, when fog oil smoke was used to conceal troop movements, beach landings, and supply lines from ground and aerial reconnaissance. Initially, military applications used industrial oil burners to produce smoke; however, each succeeding generation of smoke generator has been more effective, lighter, or more mobile than earlier models (Liss-Suter and Villaume 1978).

A variety of fog oils and other petroleum products have been used to provide white obscurant smokes. The products that have been used include SGF-1 and SGF-2 fog oil, diesel fuel, jet fuel JP-4, and kerosene. SGF-1 has not been supplied to the U.S. Army since the mid-1970s (Liss-Suter and Villaume 1978). SGF-2 fog oil is currently used for year-round obscuration needs (U.S. Army 1986). It is also described by NATO Code No. F-62 (MIL-F-12070C, Amendment 2).

The SGF-2 fog oil currently used by the U.S. Army is little changed from that used in the 1940s, except that fog oil procured at or some years prior to the time of promulgation of MIL-F-

12070C was designated "new" because the refining process was modified to reduce quantities of some of the potentially harmful components of the material.

Generally smoke is generated from pure SGF-2 fog oil; however, quantities of kerosene may be added when the ambient temperature is below freezing (U.S. Army 1975), with the quantity of kerosene increasing with decreasing temperature (see Section 2.4.1).

2.3 PHYSICAL AND CHEMICAL NATURE OF FOG OIL

Fog oil is a liquid consisting of a large number of organic compounds. The military specifications were likely selected based on both performance and availability needs, with the result that an exact formulation of SGF-2 fog oil cannot be defined. However, the general characteristics of the liquid are discussed below.

In this and subsequent sections, the generic use of the term "fog oil" will refer to either general fog oil compounds or SGF-2 fog oil. References to SGF-1 fog oil and other materials will be by specific name.

2.3.1 Physical Characteristics

The physical characteristics of fog oil are listed in MIL-F-12070C. SGF-2 fog oil is a middle distillate product of crude petroleum oil, drawn from stocks of a raw industrial lubricant oil. It is a light viscosity lubricant, sometimes called "100 pale oil", because its viscosity is similar to that of SAE 20 motor oil, and it is a pale or straw-colored liquid (Liss-Suter and Villaume 1978). Distillates may be used if they have no additives and, meet the following requirements: 320 °F (minimum) flash point; Saybolt universal viscosity at 100 °F between 110 (maximum) and 100 (minimum); 0.1% maximum carbon residue; 0.1 maximum neutralization number; and -40 °F maximum pour point. Because of the variety of crude oil source compositions, the variety of distilling and processing procedures, and the range of acceptable physical characteristics, individual batches of fog oil may differ in composition and appearance. The density of liquid SGF-2 fog oil is about 0.92 g/cm^3.

It is reasonable to assume that battlefield smoke will not consist exclusively of fog oil droplets. Fog oil may coat dust from mechanical movements and explosions and graphite flakes from generators based on the XM56, as well as other aerosols present in the battlefield. Although data are lacking on the interaction between fog oil and other windborne materials, one possible result of mixing materials is an increase of fog oil deposition to skin, eye, and upper respiratory tract surfaces relative to a pure fog oil aerosol. This increase would be expected because fog oil coating the larger dust and graphite particles would be deposited to such surfaces at increased rates.

2.3.2 Chemical Characteristics

SGF-2 fog oil contains many hydrocarbon compounds, most of which are present in quantities less than 0.1%. Although the composition of fog oil may vary with the batch, an analysis of one sample indicated it to be about 50% aliphatic and 50% aromatic compounds (Ballou 1981). However, the extent of the overlap between the compounds on the gas chromatography/mass spectroscopy chromatogram was so large as to preclude identification of all but a few compounds. Katz et al. (1980) identified 42% to 60% of samples as aliphatics that included both straight and branched chain compounds with carbon numbers between C_{12} and C_{22}. The same study measured 2- and 3-membered ring aromatic compounds also ranging between C_{12} and C_{22}. Substituted indans, tetrahydronaphthalenes, naphthalenes, and biphenyls were the principal 2-membered ring compounds. Phenanthrene, dihydrophenanthrenes, fluorenes, and acenaphthene were the 3-membered ring compounds identified.

Kerosene is a pale yellow or water-white oil liquid mixture of petroleum hydrocarbons, constituting the fifth distillation fraction of petroleum. Most of the hydrocarbons are of the methane series (10 to 16 carbon atoms per molecule) and commonly include n-dodecane, alkyl derivatives of benzene, napthalene, and 1- and 2-methyl 5,6,7,8-tetrahydronapthalene. Kerosene is insoluble in water; has a boiling point between 175 and 325 °C; has a flash point that ranges between 65 and 85 °C; and is used in lamps, stoves, and flares and as a degreaser and cleaner. The density of kerosene is about 0.80 g/cm^3. A deodorized and decolorized form of kerosene, called Deobase, is used in cosmetics and as an insect spray (MERCK 1983).

Data characterizing the chemical condition of field-generated mixed aerosols of fog oil and dust or graphite flakes are not available. The chemical stability of fog oil coatings on graphite flake particles on surfaces and in the atmosphere is not known.

2.4 MODE OF DISSEMINATION AND DISPERSION

Fog oil aerosols are generally disseminated using long-term ground-based systems. Because the aerodynamic sizes of recondensed fog oil particles are small, downwind dispersion is dependent on local meteorological conditions. Deposition rates exceed the settling velocities of the particles.

Like most fog oil smoke generators, the XM56 smoke generator, currently under design for producing graphite flake and fog oil smokes (the separately produced smokes mix downwind of the generator), is based on long-term releases. These provide support for the obscuration reinforcing system (ORS) or the large-area screening system (LASS). In contrast, smoke pots provide small-area coverage and are generally only used in the early stages of establishing large-area screens.

2.4.1 Mode of Dissemination

Fog oil aerosols are disseminated by the recondensation of vaporized liquid fog oil. Liquid fog oil is vaporized either in the hot exhaust gases from smoke-generating engines or within self-contained smudge pots that function for about 10 min. In addition to the XM56 for mixed graphite flake and fog oil smokes, other fog oil smoke generators include the XM16, M3A3, XM52, M52 (helicopter), VEESS, AN-M7 (floating smoke pot), and AN-M7A1 (floating smoke pot). Typical generation rates for the devices range between about 24 and 80 gal/h. Exceptions to this range include the M52 (900 gal/h) and the smoke pots (in which 1.5 to 2 gal are vaporized in 8 to 13 min) (U.S. Army 1986). Another generator, the VEESS was previously used to disseminate diesel fuels as obscurants using vehicle exhaust systems and requires various grades of diesel fuels to operate effectively. The nominal fog oil generation rate using an XM56 smoke generator is 80 gal/h (77 g/s); this value was used in all calculations herein.

For use in arctic conditions, fog oil is sometimes mixed with kerosene or kerosene-like products such as diesel fuel and jet fuel to improve the flowability of the resulting liquid at temperatures below 32 °F (U.S. Army 1975). The recommended volume concentration for JP-4 or kerosene is 0% above 32 °F, 25% between 0 ° and 32 °F, 40% between -25 ° and 0 °F, and 50% between -40 ° and -25 °F. The use of kerosene without a paraffin base (preferably JP4) is recommended at temperatures below 0°F. As an alternative, paraffin lumps can be strained out of kerosene before it is mixed with fog oil (U.S. Army 1975).

2.4.2 Aerodynamic Characteristics and Settling Velocity

The aerodynamic behavior of fog oil particles is not difficult to determine. This is because fog oil particles are spherical liquid droplets having aerodynamic sizes that equal their physical diameter multiplied by the square root of the specific gravity of fog oil ($SG_{SGF2} \sim 0.92$). Aerodynamic particle size distributions of fog oil aerosols vary according to the generation method and the concentration. The generation method influences the temperature at which liquid fog oil is vaporized and the dynamics of condensation. The concentration influences the rate at which droplets coagulate. The physical or count median diameters (CMD) of fog oil aerosols typically range between 0.5 and 1.0 μm; the mass median diameters (MMD) are inherently greater because of the log-normal distribution of particle sizes about the median. Given the specific gravity of fog oil, the aerodynamic mass median particle diameter (AMMD) is about 4% smaller than the MMD. In addition to AMMD, the second parameter required to identify the aerodynamic size distribution of a log-normally distributed aerosol is the geometric standard deviation (GSD).

The aerodynamic particle size distribution of fog oil aerosols has been measured by several investigators. The AMMD (GSD) ranged between 0.6 μm (1.6) and 1.3 μm (1.6) during measurements made in inhalation aerosol chambers (Ballou 1981). Measurements made by Cataldo et al. (1989) in a wind tunnel under field-simulated conditions, but using less dilution air in the vapor condensation zone, ranged from 1.6 μm (1.7) to 3.1 μm (1.7). Katz et al. (1980) measured MMD between 0.7 and 1.7 μm using a similar (inertial) sampling technique.

Assuming a CMD between 0.5 and 1.0 μm and a GSD of 1.65, the AMMD of a "typical" aerodynamic size distribution of fog oil aerosol would be between 0.9 and 1.9 μm. Because this estimate agrees well with actual measurements made in the laboratory and field, an aerosol having an AMMD of 1.4 μm and a GSD of 1.65 was used in this study in calculations of coagulation, dispersion, and deposition. Based on 90% of the aerosol mass, this particle size distribution contains particles having aerodynamic diameters between 0.6 and 3 μm, and settling velocities ranging roughly between 0.001 and 0.03 cm/s.

The particle size distribution for mixed graphite flake and fog oil aerosols is not available in the literature. However, because most fog oil coagulation will occur close to the XM56 generator, it is possible to estimate the particle size distribution of the mixed aerosol. The AMMD of such a mixed aerosol was estimated to be 2.2 μm (Driver et al. 1992a). Other parameters describing the estimated aerosol distribution include $D_{16} \sim 1$ μm (i.e., 16 % of the mass is comprised of particles smaller than ~ 1 μm) and $D_{84} \sim 7.5$ μm (i.e., 84 % of the mas is comprised of particles less than ~7.5 μm) resulting in a GSD of about 2.5 and 3 to 3.5 for particle sizes less than and greater than the AMMD, respectively. Based on the estimated particle size distribution of a mixed graphite flake and fog oil aerosol, the range of particle settling velocities is approximately 0.002 to 0.7 cm/s. This range of settling velocities corresponds to aerodynamic particle sizes of 0.7 to 15 μm, a range that includes 90% of the mass of the mixed aerosol particles. Thus oil-coated graphite flakes would settle and deposit roughly 2 to 20 times faster than fog oil particles in the absence of graphite flakes. The impact of battlefield dust is not as simple to estimate because of the greater variability in the characteristics of suspended dust.

Although it is possible to estimate the size distribution of a mixed graphite flake and fog oil aerosol, it is not possible to estimate the compositional characteristics of the particles by size. It is impossible because determination of the coagulation of fog oil on larger graphite flakes depends on many parameters, including dissemination procedures, aerosol characteristics, and meteorological conditions. The primary effect of coagulation may be to provide a partial or complete coating or film of fog oil on graphite flakes. This could alter the deposition of fog oil to the nasal regions of the respiratory tract and could influence transport, weathering, and fate of the particles in the environment.

2.4.3 Windborne Plume Dispersion

Windborne plume dispersion of fog oil aerosols is described in detail in Appendix A. In the case of a mixed aerosol, the aerodynamic size and settling velocity of mixed graphite flake and fog oil particles would be approximately similar to those of graphite flake aerosols, and the atmospheric distribution and surface deposition would also be similar. If coagulation occurs and the graphite flakes become coated with fog oil, the surface loading of the fog oil component close to the generator will potentially be greater than that of a fog oil-only aerosol.

2.5 CONCERNS AND POTENTIAL IMPACTS

Potential impacts of the windborne dispersion of fog oil aerosols include direct health effects and environmental fate and effects.

2.5.1 Direct Health Effects of Fog Oil

The aerodynamic size of fog oil droplets generated as obscurant aerosols is sufficiently small that inhalation is a route of exposure for humans. The health effects of fog oil aerosols are discussed in Section 4.2.

2.5.2 Environmental Fate and Effects

Fog oil is degraded in the environment by chemical reactions, photochemical degradation, and microbial action. At sites used once or rarely, the effects of fog oil are expected to be transitory. At regularly used sites, effects to plants and animals may occur. The environmental fate and effects of fog oil are discussed in detail in Sections 4.1, 4.3, and 4.4.

2.5.3 Secondary Impacts of Fog Oil Use

Fog oil aerosols degrade visibility. If smoke is generated near roadways, an analysis of visibility impacts should be made (Appendix A and Section 4.1.3).

Accidental spills of bulk fog oil liquid are possible. Contingency plans to contain spills should be prepared if the material is to be transported near sensitive areas (Section 3.2).

3. ENVIRONMENTAL LAWS AND REGULATIONS

3.1 AIR QUALITY

While fog oil is not specifically controlled under Clean Air Act regulations, dispersing fog oil into the air may be regulated as particulate matter less than 10 µm and/or as a hydrocarbon emission. Constituents of fog oil, if they are present in sufficient quantity, could cause fog oil to be regulated; however, obscurant field testing is unlikely to result in regulated emissions. For example, only emissions of volatile organic compounds from a point source in excess of 40 tons/yr are regulated under the "Prevention of Significant Deterioration" regulations in 40 CFR 52.21. Standards of performance for vessels storing petroleum products that emit volatile organic compounds may be applicable if the capacity of the storage vessel is sufficiently large (40 CFR 60.110).

Reactions involving hydrocarbons, nitrogen oxides, oxygen, and sunlight produce chemically and biologically active compounds that are potentially harmful to health and environment. Although concentrations of fog oil/kerosene in air are unlikely to reach levels high enough to directly impact air quality, these hydrocarbons can enter into a series of complex chemical reactions that lead to the formation of ozone, a major constituent of photochemical air pollution. Air-quality standards are related to ozone. The national standard for ozone is 235 $\mu g/m^3$ (not to be exceeded for more than 1 h/yr) (40 CFR 50.9). Ozone production from hydrocarbons is limited by the amount of nitrogen oxides (NO_x) available. Because human activities (e.g., air and vehicular traffic) introduce air pollutants such as NO_x into the airshed, specific knowledge of the amount of activity, NO_x concentrations, and the atmospheric conditions during fog oil/kerosene releases will be needed to estimate potential ozone production. If generation tests were conducted in an ozone attainment area (relatively pristine) during a prolonged air inversion while a large-scale military maneuver is conducted, sufficient NO_x emissions could be released to cause a brief diminution of air quality as a result of ozone production.

States must comply with federal standards for particulate matter less than 10 µm in diameter and for ozone pollution. The compliance status of the individual state will largely determine the severity of the regulations that may control fog oil releases. Federal visibility assessments for certain scenic areas may impact on sources near such sites.

3.2 WATER QUALITY

Discharges of oil into or upon navigable waters (which include interstate wetlands, rivers, and streams) of the United States that violate water-quality standards or cause a film or sheen on the surface of the water are prohibited (40 CFR 110.3-110.6). Procedures and other requirements have been established to prevent the discharge of harmful quantities of oil into navigable waters from facilities that store and consume oil under 40 CFR 112.1. A determination must be made to assess whether the facility that will store the fog oil could, because of its geographic location, discharge oil into navigable waters and whether a Spill Prevention Control and Countermeasure Plan may be required.

A "point discharge" of pollutants to waters of the United States could occur as a result of testing and demonstrating the fog oil. Therefore, a national pollutant discharge elimination system (NPDES) permit under the Clean Water Act may be required. Given that the fog oil will be tested on a military reservation, it is unlikely that the fog oil will affect any community water supply system. Therefore, the national primary drinking water regulations under the Safe Drinking Water Act are not applicable. No underground injection control permit is required because underground injection of the fog oil is not planned. Runoff to a sewer may create a fire or explosion hazard (Occupational Safety and Health Act).

3.3 HAZARDOUS SUBSTANCES AND HAZARDOUS WASTES

Under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) regulations Section 101(14)(F), the definition of hazardous substance excludes "petroleum, including crude oil or any fraction thereof." Fog oil does not meet the criteria of the Resource Conservation and Recovery Act (RCRA) to be a hazardous waste when discarded or disposed. As per the MIL specifications, fog oil is not a flammable/combustible liquid.

Fog oil is not regulated as a hazardous substance pursuant to the Hazardous Materials Transportation Act (HMTA) for it does not meet the definition of any hazard class.

3.4 THREATENED OR ENDANGERED SPECIES

An assessment of the region where the fog oil is demonstrated and tested should be conducted to determine whether any threatened or endangered species or their habitats will be affected.

3.5 STATE REGULATIONS

State regulations may differ from federal regulations. Therefore, state regulations should be consulted in locations where activities occur that involve fog oil.

4. ENVIRONMENTAL AND HUMAN HEALTH EFFECTS

Fog oil obscurant smokes are dispersed by wind and become sources of exposures to the environment and man. Exposure to fog oil may affect human health and the well being of wildlife, aquatic biota, and terrestrial systems. Recommended approaches to mitigate the effects of field-dispersed fog oil material are not extensive because of the natural degradation of fog oil with time and the low levels predicted to impact downwind areas. Other environmental impacts of the manufacture, use, and disposal of the material are likewise not expected to be severe, except in the cases of smoke generation in confined spaces and accidents or spills involving large quantities of the bulk material.

4.1 NATURE OF SOURCE TERM

Source terms for exposure to fog oil aerosols include both the windborne smoke itelf (inhalation and visibility effects) and terrestrial and aquatic deposits of materials (dermal exposures, water quality, and plant and animal effects). Another potential source term is the release of large quantities of bulk liquid fog oil via accidental spills. Resuspension and redistribution of materials deposited by wind are less likely than for other obscurant materials, such as brass or graphite flakes.

4.1.1 Environmental Source Term (Deposition and Resuspension)

Windborne fog oil aerosols deposit on ground and other surfaces at rates that are influenced by atmospheric conditions and surface characteristics. Deposits are distributed in a downwind direction and are generally greatest near the source, quickly decreasing as downwind distance increases. A detailed description of estimated rates and magnitudes of fog oil deposition for downwind distances between 0.1 and 40 km is presented in Appendix A. Estimates of surface mass loading for several types of atmospheric conditions range from 30 to 800 mg/m^2 1 km downwind of the source to less than 0.001 to 0.3 mg/m^2 40 km downwind. Even under worst-case atmospheric conditions, fog oil deposition was estimated to be less than 10 mg/m^2 at downwind distances greater than about 2 km. Unless the ambient wind is very steady in direction, the deposition levels predicted above will be conservative, because the windborne plume will tend to meander. The area potentially impacted by fog oil deposition should be estimated based on expected or actual fluctuations in wind direction. Often this may be ± 45° from the expected mean wind vector. For example, if the mean wind direction is known to be from the northwest, then it might be reasonable to assume that the area potentially impacted by fog oil will be bounded by the directions south and east of the source.

Fog oil droplets will deposit on soil, vegetation, water, or other surfaces. After deposition, the material will likely remain on or be incorporated into the surface; resuspension and redistribution of deposited fog oil is not likely because of the natural adhesion of the material to most surfaces. One case in which resuspension and subsequent redistribution of fog oil could occur is if deposits on dry soil were resuspended during a post-exposure dust storm. In nearly all cases of resuspension, the subsequent redistribution of fog oil would be to a larger area than the original deposit but in deposition levels much smaller than the levels at the original deposit site. Deposition of fog oil on moving bodies of water (such as streams) is a second case in which the material could be transported away from the original deposit site. Estimated deposition rates (Appendix A) combined with specific knowledge of the stream flow characteristics will allow determination of fog oil concentrations in the stream. These concentrations will be greatly attenuated shortly after smoke generation.

Most fog oil will remain at the location where it is deposited. The rate of incorporation and chemical, photochemical, and microbial degradation of the material will vary greatly depending on the characteristics of the surface and site. Volatilization of fog oil exposed to air will result in a

30% to 40% decrease in fog oil mass within a 1-h period at temperatures between 0 and 40 °C (Appendix A). Within one week, about 80% to 90% of the fog oil mass may have been evaporated. At lower temperatures, volatilization rates are much slower. These estimates of fog oil volatility were based on the assumption of 1.5-µm particles suspended in air; actual evaporation rates may vary.

4.1.2 Human Inhalation Source Term

Inhalation of windborne fog oil smoke poses a potential health risk. The air concentrations of fog oil aerosols were estimated (Appendix A) based on a single XM56 smoke generator operating under uniform atmospheric conditions. Concentrations produced by multiple, co-located generators will be roughly a scalar value of the number of generators in operation. Actual meteorological conditions will likely result in lower time-averaged air concentrations as real smoke plumes will tend to meander downwind of the generator. Based on the estimates provided in Appendix A, windborne fog oil concentrations will generally decrease from between 7 and 140 mg/m^3 at downwind distances between about 0.1 and 0.2 km, to between less than 0.003 and 0.3 mg/m^3 at a distance of 40 km. Air concentrations exceeding 10 mg/m^3, the short-term exposure limit (STEL) for fog oil (see Section 4.2), were predicted to occur within downwind distances of 0.4 km from the source during five of six meteorological cases. During the sixth case, the relatively rare case of moderately stable atmospheric conditions, the STEL could be exceeded within about 2 km of the source.

The primary determinant of inhalability of aerosols is the aerodynamic diameter of the individual particles (Miller et al. 1979). Fog oil particles are spherical and have aerodynamic sizes ranging from about 0.6 to 3 µm (see Section 2.4.2). Particles having aerodynamic diameters less than roughly 3.5 µm can penetrate effectively to the gas-exchange, or alveolar, region of the lungs and are generally considered to be respirable (ACGIH 1985). Thus, all or nearly all of the mass of fog oil aerosols are inhalable and respirable, and most inhaled fog oil particles have the potential to become deposited in all regions of the human respiratory system. Because some inhaled particles are exhaled, the total deposition of fog oil particles in the human respiratory system may range between 30% and 90% of the total amount inhaled. This conclusion is based on deposition fraction versus aerodynamic particle size data (ACGIH 1985).

4.1.3 Visibility Reduction Source Term

Fog oil smoke has the potential to cause visibility reductions. These reductions may be significant if smoke drifts across public-access roadways during testing periods. The results of an analysis of this potential for a mixed fog oil and graphite flake smoke under arctic conditions are presented in detail in Appendix A (Driver et al. 1992a). It is likely that these results are somewhat conservative because of the low temperatures assumed and the reliance on estimated plume centerline aerosol concentrations. The distances from the source for which the estimated transmittances were less than 5% (at a crosswind range of 1 km) extended from 0 to about 20 km, depending on weather conditions. This indicates that the potential for visibility reductions may extend far downrange, and should therefore be evaluated for each location having roadways within about 25 km in the primary downwind direction.

4.2 HUMAN HEALTH EFFECTS

The human health effects of fog oil exposure via respiratory, dermal, and oral routes are reviewed in this section. Toxicity and carcinogenicity data for SGF-2 are limited; therefore, information on the health effects of other lubricating oils was used to evaluate the health hazards associated with field generation of fog oil smokes. The risks of inhalation, ingestion, aspiration, and dermal exposure of fog oil are discussed.

Because fog oil can be co-generated with electromagnetic obscurants such as graphite flakes to produce smokes with broader screening ability, the potential health effects of mixed smokes of fog oil and graphite flake are also reviewed.

4.2.1 Direct Inhalation Hazards

In general, the respiratory toxicity of a petroleum hydrocarbon is inversely proportional to its viscosity (Klaassen et al. 1986). Hydrocarbons with viscosities ≤ 35 Saybolt universal seconds (SUS) pose an extreme health risk when inhaled; high-viscosity hydrocarbons (viscosity ≥ 150 SUS), such as heavy oils and greases, present only a very low respiratory risk. The viscosity of SGF-2 (100 to 110 SUS at 100 °F) appears to be in the range for low to moderate respiratory toxicity. This conclusion is borne out by toxicity studies using fog oils and other lubricating oils. Although concentrations of airborne lubricating oils in the range of 60 to 200 mg/m^3 have resulted in systemic pathologic changes, including oil pneumonitis, immunodepression, and hepatic, lung, and cardiac lesions (Selgrade et al. 1987; Brahmachari 1958; Muhly 1983), most of these lesions may in fact have been caused by additives or other contaminants in the oils. Only moderate, largely reversible respiratory changes have been observed in animals exposed to uncontaminated fog oils. Repeated exposures to airborne SGF-2 (3.5 h/day, 4 days/week for 4 to 13 weeks) at concentrations below 500 mg/m^3 resulted in minimal systemic and pulmonary changes in rats (Grose et al. 1985, 1986; Selgrade et al. 1987, 1990). Reduced body weight gain (Grose et al. 1985), increased sleep time, elevated erythrocyte count, and mild inflammatory edema in the lungs were observed in animals exposed to ≥ 500 mg/m^3; however, pulmonary function and gas exchange were not compromised (Grose et al. 1986; Selgrade et al. 1987, 1990). Comparable exposure to aerosols of mixed fog oil and graphite result in more effects than fog oil aerosols alone (Aranyi et al. 1992) and include a minor impairment of pulmonary function characterized by reduced respiratory system compliance and a decrease in static and dynamic lung volumes of the rats (Aranyi et al 1992). No mortalities, clinical signs of toxicity, body weight changes, or reduction in pulmonary bactericidal activity were observed following 4 or 13 weeks of exposure to fog oil or mixed fog oil/graphite aerosols. Subchronic exposure to 1,500 mg/m^3 of fog oil results in a progressive granulomatous lesion after the exposure has ceased. The lesion is more pronounced in male rats than in females (Grose et al. 1986; Selgrade et al. 1987). Accumulation of macrophages in alveolar spaces of the lung has been the major histopathologic effect reported in a variety of species exposed to oil mists (Lushbaugh et al. 1950; Stula and Kwon 1978; Osmitz et al. 1987). Although the acute LC_{50} (the concentration that is lethal to 50% of the rats tested) of SGF-2 aerosols in rats is relatively high, 5,200 mg/m^3, for a single 3.5-h exposure, the concentration response curve appears to be very steep. Exposure at 1500 mg/m^3 for 5 h/day resulted in 60% mortality after only 2 days. Exposure to as little as 2000 mg/m^3 for 3.5 h/day for 4 days also resulted in mortality (Selgrade et al. 1990). Inhalation studies using SGF-1 showed that chronic exposure to 63 mg/m^3 for 30 0.5 h/day for a year produced only minimal pulmonary effects in mice, rats, and rabbits. However, monkeys exposed to this concentration of SGF-1 mist suffered oil pneumonia, severe hyperplastic gastritis, and alopecia and died within 100 days (Lushbaugh et al. 1950). Whether primates have a similar sensitivity for SGF-2 is unknown.

Exposure standards for military materials are not well defined because military materials and exposure conditions are uniquely different from those in the industrial workplace. To establish safe levels for fog oil exposure, a standard substance (mineral oil) that is chemically and toxicologically similar to fog oil (Liss-Suter et al. 1978a) is used as a point of reference. It should be noted that mineral oil mists differ from fog oils in that the particle size distribution for mineral oil is submicron to about 20 μm (Hinds 1982), whereas particles in fog oil smokes typically range between submicron and 5 μm in diameter (Young et al. 1989). Mineral oils may also contain additives that are not present in fog oils.

The threshold limit value (TLV) for chronic industrial exposure to mineral oil mist during an 8-h work day is 5 mg/m^3 (ACGIH 1986). This is also the level at which fog oil mists become visible. Smoke generation exercises are usually limited to ≤ 4 hours per day. Exposure limits may be normalized as a time weighted average (TWA) to the 8-h limit to accommodate actual exposure time. For example, normalizing a 4 hour exposure to an 8-hour day would increase the allowable exposure to twice the limit (Palmer 1990). The STEL for oil mists is currently 10 mg/m^3. Generally, STELs are based on health effects and exposures at the STEL concentration should not exceed 15 minutes nor be repeated more than four times per day (ACGIH 1986). However, in this case, the STEL is based primarily on safety factors such as the prevention of slippery surfaces (Vena et al. 1985). In the ACGIH 1992-1993 TLV documentation, the notice of intended changes for mineral oil mist recommends deleting the STEL and changes the TWA for mildly refined oil mists that contain polycyclic aromatic hydrocarbons (PAHs) to 0.2 mg/m^3 (ACGIH 1992). Workers exposed to oil aerosols begin to complain of discomfort at about 15 mg/m^3 (ACGIH 1986).

Extrapulmonary effects of fog oil inhalation include the induction of a specific isoenzyme of the cytochrome P450 system, which may have significant implications in xenobiotic metabolism of exposed animals (Grose et al. 1986).

Humans within about 2 km downwind of the test site during smoke-generating periods may inhale potentially harmful levels of fog oil (i.e, ≥ 10 mg/m^3; see Section 4.1.2) if weather conditions result in a shallow mixing depth. Under conditions favoring a greater mixing depth, harmful levels are limited to within 0.4 km downwind of the generator. Exposures above 500 mg/m^3 are unlikely, except possibly for personnel operating or standing very near the generator during test generations (Appendix A). This exposure level is in agreement with measurements of breathing zone concentrations of fog oil obtained during military training missions to determine the field exposure of military personnel to fog oil smoke (Young et al. 1989). For military personnel in proximity to the generators, concentrations often exceeded safe levels, reaching about 130 mg/m^3-h under certain testing scenarios (Young et al. 1989). It should be noted that smoke generator unit personnel and military operating in constant smoke screens during WWII did not show any adverse effects from the oil exposures (Liss-Suter et al. 1978a). However, the medical review was limited to short-term health impacts and lacked information on exposure protection (e.g, the use of respirators).

4.2.2 Ingestion Effects and Aspiration Hazard

The health effects of SGF-2 ingestion have not been fully investigated. However, the toxicity of petroleum products, including lubricating oils, via oral exposure is generally low. The acute oral LD_{50} (the dose resulting in 50% mortality of the test population) for diesel oil is 16 ml/kg in rats (Starek et al. 1975). Between 5 and 20 ml/kg of white mineral oil (similar to, though more refined than SGF-2) are required to cause mortality in laboratory mice (Brahmachari 1958). The oral LD_{50} for kerosene is 30 ml/kg for rats (Ashkenazi and Berman 1961), 28 ml/kg for rabbits (Deichmann et al. 1944), and 20 ml/kg for guinea pigs (Deichmann et al. 1944). Oral ingestion of 5 to 20 ml/kg of mineral oil by rodents resulted in weight loss and histopathological lesions of the liver, spleen, and kidney (Brahmachari 1958). Fog oil appears to have an acute LD_{50} in rats in excess of 5 g/kg (4.5 ml/kg) (Mayhew et al. 1986).

Although ingestion of harmful amounts of fog oil is unlikely, it should be noted that aspiration of the oil into the lung during or after consumption can be very hazardous. Indeed, the most serious consequence of oil ingestion is aspiration pneumonia (Buck et al. 1982). Aspiration of a petroleum product is often many times as lethal as ingestion of the oil in the absence of aspiration. For example, intratracheal administration of 0.2 ml/kg of kerosene resulted in about 50% mortality of a test group (Gerarde 1959), whereas 30 ml/kg would be required to cause death by ingestion alone (Ashkenazi and Berman 1961). Pathologies associated with aspirated oil include bronchopneumonia, acute pulmonary edema, and visceral congestion (Brahmachari 1958; Buck et al. 1982). The pulmonary lesions are distributed bilaterally and are usually observed in the caudoventral apical, cardiac, cranioventral diaphragmatic and intermediate lobes (Buck et al. 1982; Gerarde 1959). Multiple pulmonary abscesses have been found in animals surviving several days after aspiration (Buck et al. 1982). Children suffering from kerosene and crude oil aspiration toxicosis experience central nervous system derangement in the form of incoordination, shivering, head shaking, and confusion. Anorexia, weight loss, and low blood glucose are common in animals that have aspirated petroleum products. In addition, the hematologic and blood chemistry changes associated with pneumonia are present. These include elevated packed cell volume (PCV) and hemoglobin levels, increased blood urea nitrogen (BUN) and serum transaminase enzymes, leucopenia, and accumulation of macrophages in alveolar spaces of the lung (Lushbaugh et al. 1950; Stula and Kwon 1978; Buck et al. 1982; Osmitz et al. 1987; Selgrade et al. 1990). Although oil aspiration toxicosis has occured in humans, the poisonings were accidental or occurred in young children. Adherence to basic health protection practices by personnel during test releases will eliminate ingestion and aspiration exposure.

4.2.3 Dermal Effects

In general, repeated or prolonged dermal exposure to petroleum products (e.g., as a result of continued wearing of oil-soaked clothing) can break down the protective defences of the skin barrier, causing inflammation, acanthosis, and eczema (Liss-Suter et al. 1978a; Smith et al. 1987). Skin conditions such as acne are common among industrial workers exposed to lubricating oil mists (Liss-Suter and Villaume 1978). However, dermatitis caused by petroleum products commonly regresses spontaneously if exposure is discontinued (Gehring et al. 1991). With a Primary Irritation Score of 3.8, SGF-2 is considered to be moderately irritating to skin (Mayhew et al. 1986). Erythema (grades 1 through 3), edema (grades 1 through 4) and desquamation were observed in test animals; however, all clinical signs of irritation were resolved by the sixth day of evaluation. Fog oils used for obscuration (i.e., SGF-2) are not considered to be skin sensitizers or eye irritants (Manthei et al. 1980; Mayhew et al. 1986; Smith et al. 1987).

4.2.4 Carcinogenicity/Mutagenicity

Fog oils include classes of refined oil that have been shown to induce skin tumors in laboratory animals and to increase the incidence of skin squamous cell carcinomas in nonmilitary workers (Liss-Suter and Villaume 1978; U.S. Army 1986). According to the mineral oil classification of the International Agency for Research on Cancer (IARC 1984), SGF-2 is derived from solvent-refined oils (class 3) and from hydrotreated oils (class 4). Both of these classes of oils have produced dermal cancer in experimental animals (Liss-Suter and Villaume 1978) and are unequivocally associated with skin and scrotum cancer in humans (Cruicshank and Squire 1950, Bingham et al. 1980, Hendricks et al. 1962, Hodgson 1970). However, the carcinogenicity of napthenic and paraffinic stock oils appears to be related to the concentration of polycyclic aromatic hydrocarbons in the oil (Pereira 1983, Bingham et al. 1980, Falk et al. 1964), and the military now limits purchase of SGF-2 to oils with minimal potential for containing these carcinogenic compounds. The Military Specifications for fog oil were modified in 1986 to exclude all "carcinogenic or potentially carcinogenic constituents". Oil processed with severe solvent refining or hydrotreatment as specified by OSHA (1985) has been assumed to meet the 1986 specifications and is referred to as "new" fog oil. Pre-1986 fog oil is referred to as "old" fog oil and use of this conventionally refined fog oil is not recommended (Palmer 1990). It should be noted that process parameters specified by OSHA do not necessarily ensure that oil stocks are carcinogen-free

(Palmer 1990). Indeed, the carcinogenicity and mutagenicity of fog oils processed in accordance with the OSHA specifications have been reported (Halder et al. 1984, Haas et al. 1987). Despite extended exposure to "old" fog oil smoke screens during W.W.II, no carcinogenic or mutagenic effects were detected in troops in subsequent epidemiological studies (McNamara 1963; Butler 1974, as reported by Liss-Suter et al. 1978b). This epidemiological evaluation, however, is lacking somewhat in documentation and medical follow-up on exposed personnel.

Although it is difficult to induce pulmonary cancer in experimental animals with polycyclic hydrocarbons and the incidence of lung cancer in humans exposed occupationally to these compounds is very low (Falk et al 1964), the noncarcinogenicity of chronic respiratory exposure to fog oils has not been established.

Chronic oral uptake of highly refined oils is not tumorgenic in laboratory animals (Roush et al. 1980).

Mutagenic substances are formed during the enzymatic breakdown of some aromatic hydrocarbons found in oils similar to SGF-2 (Liss-Suter and Villaume 1978). The SGF-2 specifications apparently eliminate these compounds, given that the laboratory mutagenicity tests for SGF-2 are negative (Lee et al. 1989). However, SGF-2 has been found to be weakly mutagenic in native rodents exposed in the field (Yanders et al. 1985). This study was conducted with the "old" fog oil and may have contained mutagenic substances.

4.2.5 Visibility Hazard

Hazardous driving conditions can be produced by fog oil plumes within about 25 km of the test site depending on weather conditions (Driver et al. 1992a, b). Within this range, it is possible for light transmittance to be reduced to 5% or less, the point at which a target is always obscured.

4.2.6 Fire and Explosion Hazard

Although fog oil is a flammable and combustible liquid, a smoke cloud comprised of fog oil droplets will not ignite. A typical fog oil obscurant cloud has a fuel-air ratio that is about four orders of magnitude less than the lowest amount of vaporized fuel in air that will give a combustible mixture (Sullivan and Reitz 1980). Risk of explosion is also minimal because the lean deflagration limit of fuels is smaller than the lean explosive limit and, in general, fuels are not detonable except in an enclosed space.

4.3 TERRESTRIAL EFFECTS

The use of fog oil aerosols as obscurants can impact three major components of the terrestrial system: the soils (and associated microbial and invertebrate communities), the vegetation, and the vertebrate fauna. Fog oil residues will eventually be deposited on the surfaces of leaves and in and on the soils, which function as a major sink for such materials. Wildlife may take up harmful levels of fog oil by consuming contaminated vegetation and soil, inhaling airborne oil droplets, or ingesting fog oil residues from grooming or preening.

4.3.1 Fate and Effects in Plants

The deposition of fog oil to plant surfaces appears to depend on canopy type (Cataldo et al. 1989). Values for mass loading and deposition velocities of fog oil were higher for pines and sagebrush than for fescue and bush bean. However, as reported for soils, the depuration rate of fog oil residues from plant surfaces is high; rapid losses result from volatilization from relatively large foliar surface areas.

Phytotoxicity of Deposited Fog Oils

Fog oils deposited to foliar surfaces cause moderate toxicity responses, i.e., chlorosis, necrotic spotting of foliage, and leaf or needle burn (Cataldo et al. 1989). These responses occur after deposited doses of 100 to 500 µg fog oil/cm^2 on soil. In general, older growth is affected more severely than younger growth. Results of Cataldo et al. (1989) indicate that the effects of fog oil exposure were more severe for perennial grass species than for woody species tested.

Aliphatic hydrocarbons, which are the major constituents of fog oil, are less phytotoxic than the aromatic hydrocarbons; however, the aliphatic hydrocarbons can affect membrane/cell permeability and probably account for the observed damage to foliage. The toxicity responses probably result from osmotic damage.

Other tests showed that once fog oil is deposited, subsequent rainfall is not effective in washing the material from the foliage. However, at high humidities, when leaf cuticle materials are fully hydrated, fog oil residues apparently cannot penetrate the cuticle as easily and toxic responses are less severe.

The cumulative effects to foliage of repeated doses of fog oil (low dosage=17 to 32 µg fog oil/cm^2 foliage; high dosage=242 to 754 µg fog oil/cm^2 foliage) at 2- to 3-day intervals caused less damage to plants than expected (Cataldo et al. 1989). The rapid volatilization of fog oil from foliar surfaces appears to decrease the impact of deposited materials by decreasing the final dosage. However, Cataldo et al. did not observe any evidence that the plant species tested would be able to acclimate or compensate for repeated chemical insult.

Residual and Indirect Effects of Fog Oil Deposition on Plant Growth

The deposition of fog oil on foliar surfaces results in foliar absorption and transfer of smoke constituents to below-ground plant tissues. Cataldo et al. (1989) indicated that this accumulation and transfer impacted subsequent biomass production in a perennial grass. Because the hydrocarbons that are responsible are normally biodegradable, these residual effects should attenuate with time.

Deposition and accumulation of fog oil on soils can have indirect effects on plant growth (Cataldo et al. 1989). Although few visual symptoms of toxicity appeared, plant biomass production was reduced when plants were grown at low relative humidity (20%) in soils exposed to fog oils. It may be that leaf surfaces not fully hydrated as a result of water stress are more easily penetrated by fog oil, resulting in damage to cell membranes. Some evidence exists that plants under water stress may be subject to increased toxic effects, if the fog oil residues in the soil inhibit transport of water from roots to leaves. The observed biomass effects were also dependent on soil type (i.e., soil texture). In addition, no effect of fog oil residues on seed germination or soil nutrient levels was apparent (Cataldo et al. 1989).

4.3.2 Fate in Soils

Fog oil aerosol residues deposited to soil surfaces are volatilized rapidly (Cataldo et al. 1989). Depuration rates may differ in soils of differing porosity; finer-textured soils, which have higher surface areas, may allow more sorption and thus a higher rate of initial volatilization.

Coarser soils may allow more downward leaching of deposited residues and less initial volatilization (Cataldo et al. 1989). Thus, the retention of fog oil may vary by soil type. The hydrocarbons composing the fog oil residue are biodegradable and would be attenuated over time.

Soil Microbial Effects

The soil microbial population plays a critical role in decomposing organic matter and in the cycling of important nutrients (nitrogen, phosphorus, sulfur, and some trace metals). Microbial decomposition processes in the soil can also detoxify xenobiotic chemicals. Any physical or chemical perturbation to the soil system that impacts the microbial processes impacts the soil system and the plants growing in that substrate. Some obscurant smokes adversely affect soil microbe processes (Van Voris et al. 1987). However, Cataldo et al. (1989) reported no deleterious effects of fog oil residues on soil microbial activity. High cumulative doses (1,100 μg fog oil/cm^2) of fog oil exposure had no effect on soil respiration, and only slightly increased the activity of nitrobacter populations in one soil. The cumulative dose of fog oil greatly increased soil dehydrogenase activity. These results indicate that fog oil has no deleterious effects on soil microbes even at levels far exceeding predicted worst-case surface deposition (i.e., up to 130 μg/cm^2 for fog oil) (Section 4.1.1).

Invertebrates

The earthworm is an important soil invertebrate in many soil systems, functioning to maintain soil aeration, increase water infiltration, and break down soil organic matter. Earthworm bioassays conducted with fog oil residues (Cataldo et al. 1989) showed no adverse effects of fog oil on either cocoon hatch or survival of young or adults at surface deposition rates of up to 800 μg/cm^2. Earthworm survival was 100% in soil that was uniformly amended with over 285 μg/g fog oil, which is equivalent to an aerial-deposition dose of about 3,600 μg/cm^2. These no-effect levels are 2 to 28 times as high as maximum deposition rates for fog oil or mixed graphite/fog oil.

Impacts to invertebrates above ground might occur, if insects are coated with fog oils. Such impacts would be limited to the immediate area of the fog-oil-generating source and would not likely impact insect populations. The volatile nature of the constituents of fog oil aerosols suggests that any impacts would be attenuated rapidly.

4.3.3 Wildlife Effects

There are no data available on the toxicity of SGF-2 to wildlife. At this time, the toxic effects of SGF-2 to wild birds and mammals can only be inferred from oil-spill studies. The impacts of ingestion, oil-coating, food chain bioaccumulation, and inhalation of petroleum products are discussed. Inhalation of fog oil aerosols has been investigated in human surrogate species (e.g. the rat) and harmful exposure levels extrapolated for humans. However, application of these values to the wide variety of wild animal species is problematic. Avian mortality estimates have been made for oil-spill exposures and are used here to estimate the potential risk to avian populations associated with fog oil generations or spills at test sites.

Inhalation Effects

Wildlife remaining within about 2 km downwind of the test site during smoke-generation may inhale potentially harmful levels of fog oil (i.e, $\geq$ 10 mg/m^3; see Section 4.1.2) if weather conditions result in a shallow mixing depth. Under conditions favoring a greater mixing depth, harmful levels occur only within 0.4 km downwind of the generator. This assumes that wild animals have about the same sensitivity to air pollutants as humans and receive (on a body-weight basis) equivalent doses in the environment. However, it has been shown that the volume of air breathed per minute per unit of body weight (i.e., the weight-specific minute ventilation) varies greatly among mammals (Phalen 1984). Generally, the smaller the animal, the more air per minute per gram is inhaled. Compared to humans, rabbits ventilate 3 times the volume of air and small rodents ventilate 8 to 13 times the volume, on a per-body-weight basis (Phalen 1984). Larger animals such as deer and moose receive smaller doses than humans during inhalation exposures. Birds may be at greater risk than represented in the human STELs because their respiratory rates are generally higher than mammals of comparable size. Seasonal physiological changes, differences in activities (e.g., flying), and breathing-zone differences (e.g., near the turbulent ground surface) further complicate the extrapolation of the human STELs to wild animals. Therefore, the STELs for humans should be viewed as only relative estimates of the safe limits for wildlife in field situations.

Ingestion Effects

There are no specific data available on the toxicity of fog oil ingestion to wildlife. Information on the toxic effects of petroleum products in wild mammals and birds is available from oil-spill studies. The acute oral LD_{50} of diesel oil is 16 ml/kg for rats (Starek et al. 1975). Oral ingestion of 5 to 20 ml/kg of mineral oil by rodents resulted in weight loss and histopathological lesions of the liver, spleen, and kidney. All animals died within 10 days (Brahmachari 1958). However, intragastric administration of 24 ml/kg of diesel fuel did not result in mortalities to ducks (Hartung and Hunt 1966). Under temperature stress, the intragastric LD_{50} in ducks was lowered to 4 ml/kg (Hartung and Hunt 1966). Like birds, water-living mammals (e.g., otters and seals) appear more vulnerable to oil exposure when they are also otherwise stressed (Geraci and Smith 1977). Stress conditions typically include disease, heavy parasitization, advanced age, vulnerable life-cycle stages, nutritional status, and social status (e.g., isolation). The increased vulnerability caused by stress is probably related to adrenal insufficiency (Geraci 1972).

A bird found in the vicinity of an oil spill has, on average, about 7 g of oil on its feathers and ingests, from preening, about 1.5 g (2 to 3 g/kg) of oil in one day (Hartung and Hunt 1966). In birds ingesting this amount of oil, lipid pneumonia, gastrointestinal irritation, diarrhea, anemia, altered liver function, internal hemorrhage, severe pancreatic damage, and toxic nephrosis have been observed (Hartung and Hunt 1966; Chia 1971). These clinical signs have been observed both in wild ducks killed in oil spills and in waterfowl receiving intragastric doses of 1 to 12 ml/kg of diesel fuel (Hartung and Hunt 1966). At levels above 5 ml/kg, nervous system effects (including inhibition of plasma cholinesterase) mimic those induced by anticholinesterase agents and may be caused by phosphorus compounds in the oils (Holmes and Cronshaw 1977). It should be noted that other investigators have not been able to induce most of these pathological changes in waterfowl dosed with various crude or lubricating oils (Clark and Kennedy 1968; Crocker et al. 1974, 1975). However, they have observed some gastrointestinal injury and a hyperadrenocortical condition that may account for the high mortality in cold-stressed birds (Clark and Kennedy 1968; Crocker et al. 1974, 1975; Holmes and Cronshaw 1977). A review of bird mortalities following oil spills suggests that refined petroleum products, such as lubricating oils, may be more hazardous to birds than crude oil (Holmes and Cronshaw 1977).

Ingested oil may also affect the fecundity of birds. Oral administration of 3.5 mg/kg of No. 2 diesel fuel oil to quail interrupted egg production and produced egg yolk deposition anomalies (Grau et al. 1977). Ingestion of the more refined petroleum product, mineral oil, did not affect the rate of egg laying or the hatchability of eggs. Embryonic development is known to be arrested in pheasant, gull, and duck eggs sprayed with diesel fuel (Bourne and Devlin 1969; Kopischke 1972). Eggs contaminated by oils from feathers of incubating parents also do not hatch (Birkhead et al 1973). To determine if the embryonic mortality from external exposures to oils was caused by a reduction in gas exchange from the coated egg surface or by the toxicity of the oil constituents, several studies limited the oil exposure to small volumes applied over different percentages of the surface area of the dosed eggs. Significant mortality was observed when 1 μl of No. 2 fuel oil was applied to less than 2% of the shell surface (Albers 1976; Szaro and Albers 1976), indicating the embryotoxic capacity of the lubricating oils.

Ingestion of oils by seals results in minimal, transient liver damage (Smith and Geraci 1975; Geraci and Smith 1976, 1977). On the other hand, liver damage in domestic animals is well documented (Cornelius and Kaneko 1963). The most serious consequence of oil ingestion in terrestrial mammals is aspiration pneumonia. This lethal condition occurs in cattle following multiple doses that total more than 56 ml/kg for kerosene and 74 ml/kg for crude oil high in gas oil and lubricating distillates (Rowe et al. 1973). Anorexia and weight loss for several days or weeks are common clinical signs in mammals exposed orally to petroleum oils (Buck et al. 1982). Blood glucose levels are correspondingly decreased and hematologic changes associated with pneumonia (see Section 4.2.2) are typical (Buck et al. 1982). Central nervous system dysfunction has been observed in young animals exposed to petroleum oils (Buck et al. 1982). Acute enteritis, enteric edema, renal hyperemia, and acute cystitis have been observed in bovids which, because they lack gustatory discrimination, will consume large amounts of oil (Jones and Hunt 1983). Aspiration of petroleum oils is the major hazard of oil ingestion and results in lung lesions and death at concentrations much lower than would be required to adversely impact the health of an animal ingesting oil without aspiration (see Section 4.2.2).

Food Chain Effects

Lubricating oils similar to SGF-2 have been shown to bioaccumulate in aquatic food chains with mammalian top consumers (Smith et al. 1987). Palatability of the tainted food source is greatly affected for human consumers (Mackie et al. 1972), which may imply reduced palatability and, thus, reduced food source for wild mammals. Birds, however, do not avoid oil-contaminated food or habitats (Holmes and Cronshaw 1977). Oils also concentrate fat-soluble compounds, such as pesticides, and may make these compounds available at much higher concentrations than would occur in the absence of the oil and available to animals not typically exposed to them (Blumer et al. 1971). If all of the surface-deposited fog oil is assumed to be deposited on edible biomass, oral uptake of fog oil by wildlife feeding on oil-contaminated plants can be estimated, using a forage consumption factor of 3% of the body weight (Buck et al. 1982) and the edible biomass estimate of the relevant plant communities. (This estimate of oral uptake does not take into account indirect ingestion via grooming/preening.) Depending on the weather conditions and amount of fog oil generated, the consumption of oil deposited near the source may exceed toxic levels. The threat to foraging wildlife will persist until deposits are diminished by evaporation and degradation. However, areas having deposits high enough to be threatening would likely be small and, consequently, the number of potentially impacted animals would also be small (Driver et al. 1992a). Loss of aquatic food sources (see Section 4.4) may affect the survivability of aquatic wildlife, such as waterfowl young, that are dependent on limited local resources and have high nutrient requirements during their initial growth period.

Oil-Coating Effects

Pollution of water systems with oil can harm waterfowl by coating their feathers, resulting in cold shock, loss of buoyancy, and increased vulnerability to predation, starvation, and drowning (Hunt and Ewing 1953). Contamination of bird feathers with oil can cause the bird to expend much more energy to maintain body temperature. At 15°C, the basal metabolic rate of a 900-g black duck with 20 g of lubricating oil on its feathers is double the normal rate (Hartung 1967). This rate of energy consumption is equivalent to that of an uncontaminated bird at -10°C. Therefore, a bird that is moderately contaminated with a lubricating oil would have to double its food intake to offset the loss of thermal insulation (Hartung 1967).

Aquatic mammals vary in their dependence on fur insulation and, thus, their vulnerability to cold if their fur is oil covered. For instance, because fur does not contribute significantly to the overall insulation of phocid seals, no thermoregulatory problems occur in adult seals contaminated with oil. However, otarid seals, otters, and very young pups of phocid seals are more dependent on the insulative property of fur than blubber for thermoregulation (Hartung 1967; McEwan et al. 1974) and may be more susceptible to loss of thermal insulation. Eye damage has been observed in seals exposed to oil spills and is a function of exposure time and concentration of volatile components (Geraci and Smith 1977). The impact of oil exposure on cetaceans is not well documented. Surface accumulation of oil is unlikely in cetaceans; however, eye damage and the cumulative influence of oil with stress may impact these mammals.

Carcinogenicity and Mutagencity

Carcinogenicity of fog oils in wildlife populations has not been addressed. However, SGF-2 has been shown to be weakly mutagenic to native rodents exposed in the field (Yanders et al. 1985).

Avian Mortality Estimates

Seabird deaths associated with marine oil spills range from 0.3 bird per ton of oil to about 90 birds per ton of oil spilled (Holmes and Cronshaw 1977). The number of deaths is dependent on the presence of colonial species and seasonal migrants (i.e., large numbers of birds being congregated in a small area), weather, and, possibly, fuel type (Holmes and Cronshaw 1977). Typical generations using the XM56 emit about 310 lbs of oil per 30 min. If all the fog oil needed for one 30-min generation were spilled into a waterway (and assuming that the toxicity of fog oil is similar to that of the diesel fuels), about 15 birds could be killed. It is unlikely, however, that aerosol deposition from one generation, even if conducted near a body of water, will result in significant bird loss. Under worst-case generation conditions (Appendix A), surface deposition to a one-acre lake located near the source and following 9 h and 30 h of generation is estimated to cause about 9 and 31 waterfowl deaths, respectively. The impact of these deaths depends on the population status of the species. For example, the population stability of species with critically low populations (endangered species) might be affected by a small increase in mortality; therefore, environmental releases of fog oil should be avoided when such species are present. Under more favorable generation conditions (i.e., Cases 1 and 2, Appendix A), deposition of fog oil to water near the generators after 9 h or 30 h of emissions would likely result in less than one waterfowl death. Fog oil deposition to water systems farther than about 1 km from the source (see Section 4.1.1) should not be sufficient to cause significant impact to wildlife from coating of fur or feathers. However, evaporative loss of the oil may be greatly reduced under climatic conditions of extreme cold, and consequently the deposition of fog oil to water systems at greater distances would increase. There is also a potential in cold regions for fog oil to enter water systems during spring thaw, as a result of the run-off of winter-deposited oil.

4.4 AQUATIC EFFECTS

The effects of fog oils on the aquatic environment depend upon the solubility of the material in water, its toxicity to aquatic life, and the amount of material deposited into the body of water (Shinn et al. 1985). This section reviews published data regarding the impacts of fog oil obscurant on freshwater and marine environments. Little information is available on the effects of SGF-2 on aquatic systems; however, SGF-2 is physically and chemically similar to No. 2 fuel oil and to diesel fuel (Liss-Suter et al. 1978b). Therefore, literature regarding the effects of No. 2 fuel oil and diesel fuel was reviewed to further evaluate the environmental fate and the effects of fog oils on aquatic organisms.

4.4.1 Occurrence, Dispersion, and Persistence

An evaluation of the effects of fog oil on aquatic systems is dependent on the amount of oil and the way that oil enters the body of water (Shinn et al. 1985). Many processes such as photolysis, dissolution, sedimentation, biological transformation, bioconcentration of hydrophobic constituents, and food chain transport influence the fate and disposition of oils in the environment (Liss-Suter and Villaume 1978).

Deposition of Fog Oil in Aquatic Systems

The mode of deposition into a body of water may influence the effects of the fog oils. Two basic scenarios are possible: an event that leads to a spill from which bulk oil enters a water body, or an aerosol application resulting from a smoke-generating device, in which the oil becomes vaporized and settles on the surface of the water body. For example, vaporized fog oil generated from one M3A3 smoke generator for one hour could, hypothetically, deposit 6 to 60 g/m^2 on the surface of a body of water (Liss-Suter and Villaume 1978). Meteorological factors, such as wind speed and direction, temperature, and humidity, are known to affect the amount of material deposited on a given surface. Additionally, smoke-screening operations may be repeated at a single location, thus increasing the amount of fog oil that accumulates in a particular area. Any material deposited on the ground could also wash into a body of water. The constituents in the run-off may be radically different than those resulting from direct deposition of the aerosol.

Oil Behavior in Water and Sediments

The short-term and long-term mobilities of fog oil in aqueous environments have been ranked relative to those of other obscurant materials (Shinn et al. 1985). The results indicate that the dissolved organic components (presumably aromatics) in SGF-2 fog oil would be slightly mobile in contrast to white and red phosphorous smokes, which are highly mobile, and to IR **(EA-5763 and EA-5769)**, which is very immobile. The solubility of fog oil is 14-52 mg/L (Shinn et al. 1985)

Soon after oil reaches an aquatic system, physical and chemical mechanisms interact to selectively fractionate or disperse the individual constituents of the oil. The fractionation of oil is significant to both its toxicity and fate in the environment. For example, although the quantities of fairly soluble aromatic hydrocarbons are small in the original oil, that water-soluble fraction will be predominantly low-molecular-weight aromatic hydrocarbons (e.g., benzene, napthalene, phenanthrenes) that are generally more acutely toxic to aquatic organisms than the soluble saturated hydrocarbon components (Jacobson and Boylan 1973; Anderson et al. 1974; Blumer et al. 1971; Blumer and Sass 1972; Coleman et al. 1984). Poston et al. (1988) conducted a series of toxicity tests with SGF-2 fog oil and demonstrated that fog oil contains mostly water-insoluble components. The soluble fraction of 0.19 to 0.35 mg/L total oil was primarily low-molecular-weight aromatic hydrocarbons.

The deposition of the insoluble constituents in the sediment may cause longer persistence of that oil fraction in the environment and increase the exposure of benthic organisms to hydrocarbons. However, the availability of fog oil constituents to aquatic organisms inhabiting the water column would decrease. The insoluble constituents may inhibit particular animal functions such as chemotaxis or feeding activity.

Weathering Processes

Regardless of how fog oil is deposited or the quantity that is deposited, complex weathering processes associated with the liquid and solid (adsorbed) phase selectively partition the constituents of the oil. (Standard acute toxicity test protocols generally ignore fractionation caused by weathering. This neglect, in turn, results in calculations of unrealistic exposure conditions.) Water concentrations of fuel oils in seawater were found to be directly related to the amount of mixing energy to which they had been subjected (Vanderhorst et al. 1976). When oil was added to a water column with very little turbulence, trace amounts of the oil were detected in the water column. When the fuel oil was added to water under highly turbulent conditions that were maintained for a 24-h period, the water concentrations of oil was linearly related ($r=0.99$) to the volume of oil added. Various researchers have used different systems to produce oil-water mixtures. Consequently, there is not a clear-cut distinction between what is truly soluble and what is a dispersion.

Zurcher and Thuer (1978) studied the influence of weathering processes on No. 2 fuel oil. Their experiments used kaolinite as the suspended solid in the oil-water aliquots. Within 15 min of mixing, the water was saturated mostly with one- and two-ring aromatic hydrocarbons, whereas the suspended solid became almost completely saturated with higher-boiling hydrocarbons (mol wt >250) within 10 h.

The two most important processes for the removal of volatiles from a body of water are evaporation and dissolution (Coleman et al. 1984). Oils entering bodies of water will usually form a surface film or slick, from which evaporation may be significant. Regnier and Scott (1975) investigated the evaporation rates of No. 2 fuel oil at 5, 10, 20, and 30°C at a constant wind speed of 21 km/min. In a darkened chamber, fuel oil samples were poured into Petri dishes to a 2-mm thickness. The evaporation rates were curvilinear, with the remaining oil concentration at a given temperature. Components with vapor pressures higher than n-octane evaporated more readily than those with lower vapor pressures. The alkanes appeared to evaporate in proportion to the total oil evaporation rate.

Persistence

Persistence of the soluble components of fog oil in natural waters depends upon many complex factors, such as the amount of oil, water temperature, sunlight, mixing energy, presence of organic matter that can absorb oil hydrocarbons, and the degree of biotransformation (Liss-Suter and Villaume 1978; Poston et al. 1986). The insoluble fraction usually accumulates in the sediment.

Gearing et al. (1980) investigated partitioning of No. 2 fuel oil in sediments and suspended particulate matter in an estuarine environment. Two experimental tanks and a control tank (5.5 m in depth and 1.8 m in diameter) held 13 m^3 of flowing seawater and 0.8 m^3 of silt clay sediment and the associated benthic biota. Untreated marine water was pulsed at 10 L/min for 12 min every 6 h to maintain populations of zooplankton that would be representative of mid-Narragansett Bay. No. 2 fuel oil was added as an oil-water dispersion to the experimental tanks twice weekly for 4 months.

Initially, the oil-dispersion and exposure water contained 70-75% saturated hydrocarbons and 25-30% aromatic hydrocarbons. The oil accumulated in the test systems at a steady rate while dispersions were being added. The concentrations of oil found in the sediments also increased, but at a much slower rate for the first 10 weeks, after which the oil sediment concentration increased rapidly. The percentage of total oil added to the ecosystems found in the sediment reached its maximum 7 days after the last dosing (at 4 months), with 48% saturated hydrocarbons and 17% aromatic hydrocarbons in one tank and 56% saturated hydrocarbons and 9% aromatic hydrocarbons in the other. A rapid decrease of sediment oil was observed over the next 6-10 weeks. At 10 weeks, both tanks contained 14% saturated hydrocarbons and 8% aromatic hydrocarbons of sediment oil.

These proportions indicate a change from the original combination of saturated and aromatic hydrocarbons. Additionally, the aromatic constituents in the sediment were mostly the high-molecular-weight hydrocarbons, whereas the saturated hydrocarbons remained basically the same. The researchers attribute this change to the aqueous solubility of aromatics as compared to the saturates. Evaporation loss of hydrocarbons was negligible.

The concentration of oil in sediments was inversely related to the sediment depth, with the greatest amounts occurring at the sediment-water interface, which was nearly 1 cm thick after 6 months. The maximum depth of oil permeation was 3 cm.

Oil associated with the suspended particulate matter samples from the control tank approached the lower concentrations reported for mid-Narragansett Bay. The saturated hydrocarbons associated with particulates in the experimental tanks were always higher than their aromatic counterparts. The higher-molecular-weight aromatic constituents were found in the oiled sediments. The particulate bound hydrocarbons in water sorbed to suspended matter in an inverse proportion to their degree of aqueous solubility. Settling of the particulate matter resulted in deposition of about 50% of the relatively insoluble saturated hydrocarbons and less than 20% of the more soluble aromatic hydrocarbons.

The study described above also noted that biodegradation of hydrocarbons began almost immediately after they entered the sediment and that many of the compounds disappeared soon after the oil source was removed. Microbial activity appeared to degrade the saturated hydrocarbons more readily than the aromatic hydrocarbons. However, a residue (10-20% of the hydrocarbons originally present in the sediment) of branched alkanes, cycloalkanes, and aromatics and an unresolved complex mixture remained in the sediments for at least one year after the end of the experiment.

4.4.2 Toxicity

Fog oil may exert acute or chronic toxic effects on aquatic organisms Only acute effects, however, have been extensively examined. The toxicity of the individual constituents in fog oil are highly variable. Two types of adverse effects to organisms could result from the release of fog oil into an aquatic system: physical effects caused by contact with the oil, and toxicity caused by the chemical constituents of the oil. In general, the aromatic hydrocarbon fraction of the oil, particularly the polycyclic aromatic hydrocarbons (PAHs) such as the naphthalenes and phenanthrenes, poses the greatest hazard to the aquatic environment with respect to both toxicity and persistence (Poston et al. 1988; Anderson et al. 1974; Scheier and Gominger 1976; Rossi et al. 1976). Figure 1 summarizes selected data to show the range of acute and sub-acute toxic responses in routinely tested aquatic species for both No. 2 fuel oil and SGF-2.

Shinn et al. (1985) evaluated the relative toxicities of several smoke and obscurant materials on aquatic systems. The ranking was performed by using the aquatic toxicity quotient (ATQ). The ATQ was defined as the ratio of 3.6 mg/L to the median tolerance limit for 96-h LC_{50} fish bioassays. The 3.6 mg/L was an estimate of the amount of smoke products deposited in water 1 m deep from a 1-h exposure to a smoke/air concentration of 1000 mg/m^3 of aerosol. The 96-h LC_{50} is that concentration of the substance in water that results in 50% mortality of a given population of an organism after 96 h of exposure to the solution. Fog oil was found to have borderline aquatic toxicity with a 96-h LC_{50} of 2 to 50 mg/L and an ATQ of 0.72 to 1.8. Diesel fuel was identified as having the same 96-h LC_{50} and ATQ values as fog oil. The validity of this approach is suspect when one considers the complexity of these different aerosols and the reported range of solubility of the individual constituents in fog oil.

In many cases, researchers report toxicity of fuel oils at concentrations exceeding the oils' solubility. This practice may cloud the interpretation of their research with respect to pure toxicity and physical effects. Some studies report toxic concentrations of the petroleum for "total oil" and others report them for the "water-soluble fraction." The total oil concentration is the total amount of oil added to water, whereas the water-soluble fraction is the fraction of total oil that presumably goes into solution.

The water-soluble fraction of petroleum oil has been associated with sublethal effects in aquatic organisms. Lee and Nicol (1977) reported a loss of feeding activity by the planktonic shrimp, *Lucifer faxoni*. Percy and Mullin (1977) reported that minute dispersions (25 µl of oil in 500 ml seawater) reduced locomotor activity of the Arctic amphipod, *Onisimus affinis* , by about 42%. The dissolved components of oil, particularly the PAH, inhibited chemoreception in several marine animals (Lee et al. 1981). Some laboratory studies have also demonstrated that swimming behavior, growth rates, and feeding behavior are adversely affected by the water-soluble fraction of petroleum hydrocarbons (Takahashi and Kittredge 1973).

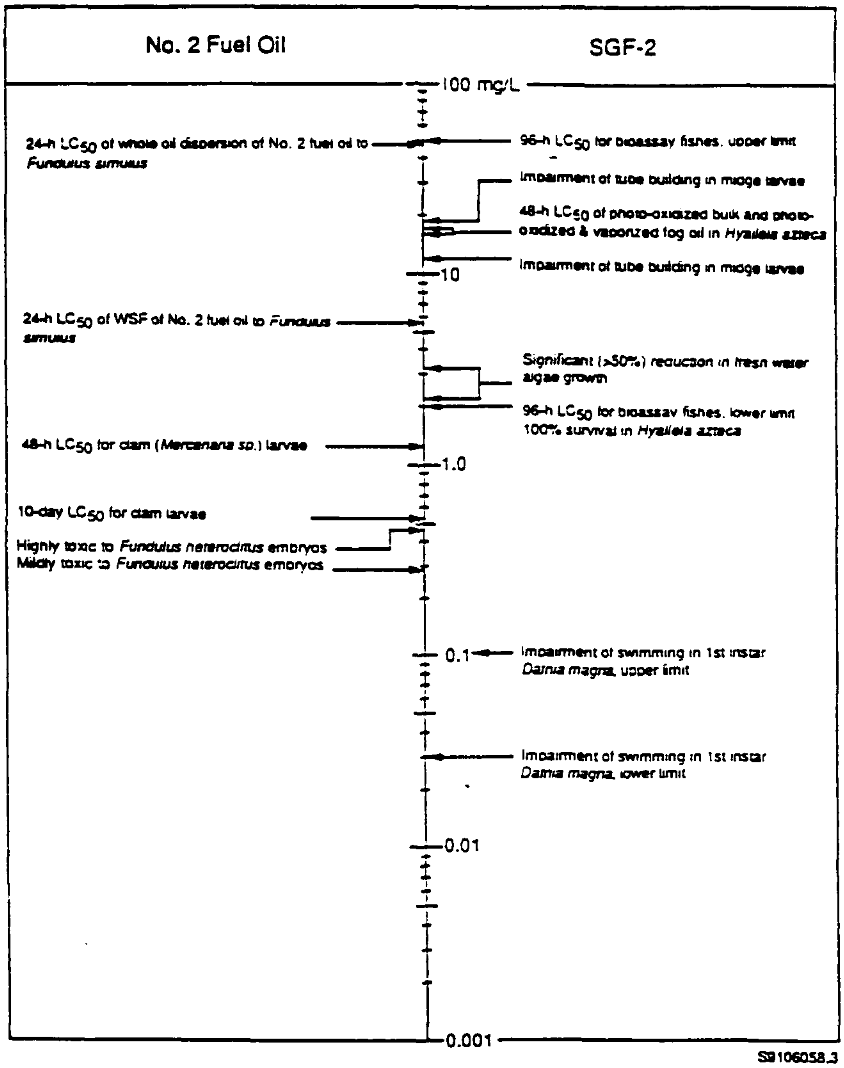

Figure 1. Range of acute and subacute toxic responses of routinely tested aquatic organisms to No. 2 fuel oil and SGF-2 fog oil.

Due to the lack of data on environmental concentrations of fog oils and associated effects, laboratory toxicity testing provides the basis for evaluating toxicity. This review covers freshwater and marine organisms separately.

Freshwater Organisms

Algae: Poston et al. (1986) performed toxicity tests with *Selenastrum capricornutum* on oil-water dispersions of bulk and vaporized SGF-2 fog oil. Bulk fog oil is unused fog oil taken straight from the barrel. Vaporized fog oil was processed through a device simulating the operation of a M3A3 fog generator and collected after condensation on stainless steel trays. Three batches of SGF-2 fog oil were tested. Five exposure solutions and a control solution were prepared for testing from each batch of stock oil. Oil-water mixtures were prepared in 10-L amounts using a standard low-energy mixing system. Tests were conducted at 22-26°C. In all but one of the algal tests, differences in treatments did not become apparent until 96 h of exposure. Concentrations between 2.15 and 3.23 mg/L total oil resulted in a 65% reduction in growth. Vaporized fog oil and bulk fog oil showed no discernible differences in growth inhibition.

Invertebrates: Poston et al. (1986) performed acute, static toxicity tests with four species of freshwater invertebrates (*Daphnia magna*, *Paratanytarsus dissimilus*, *Hyallela azteca*, *Hexagenia* sp.). During the tests, if the oil was mixed with water at concentrations greater than 1 mg/L total oil, the fog oil separated and floated to the surface. The most significant effect of the fog oil was to physically impede the movement of the organisms. Impairment of swimming was observed in first instar *D. magna* at nominal concentrations of 0.03 to 0.10 mg/L total oil. These filter-feeding organisms entrained fog oil microdroplets, which increased their buoyancy and caused them to float to the surface.

Toxicity of vaporized fog oil to *D. magna* was compared to the toxicity of fog oil (Poston et al. 1986). Concentrations of 8.96 mg/L total oil were observed to be 100% lethal in the vaporized form, whereas bulk oil concentrations as high as 30.6 mg/L were only 80% lethal. This suggests that the vaporized oil form was more toxic to *D. magna* than bulk oil form. These exposure concentrations greatly exceed the estimated solubility of the oil in water, and associated effects may not be totally attributable to chemical toxicity. In contrast, tests with midge fly larvae (*P. dissimilus*) indicated that bulk fog oil was more toxic than vaporized fog oil. A marked decrease in the number of larval tubes constructed, as well as a decrease in the length of tubes, was noted with increasing concentrations of fog oil in both forms. Mortality and tube construction were noticeably affected at approximately 12 mg/L total oil in bulk form and 17 mg/L total oil in the vaporized form. Tests with *H. azteca* indicated no toxicological differences between vaporized and bulk fog oil. Concentrations up to 14.8 mg/L bulk form were not acutely toxic, and the highest vaporized concentrations tested (5.58 mg/L) produced only 5% mortality after 48 h. Toxicity tests with *Hexagenia* sp. were inconclusive because the highest concentration tested was about 3 to 5 mg/L total oil and the observed mortality was not dose dependent.

Dauble et al. (1983) compared the relative toxicities of fog oil and several other organic liquids to *D. magna*. The SGF-2 fog oil was comparable to or less toxic than Prudhoe Bay crude oil or No. 2 diesel fuel oil. This comparison was based on toxicity tests in the same facility under similar conditions.

Fish: A series of screening tests with fog oil were conducted with fathead minnow (*Pimephales promelas*) at concentrations ranging from 0.16 to 2.37 mg/L (Poston et al. 1986). Other species were not tested with fog oil because the screening tests were negative. After 24 h, fog oil slicks formed in all test exposure solutions, indicating that the amount of oil present at the start of the tests exceeded the solubility of fog oil in water. This observation suggests that soluble components of fog oil are not present in toxic quantities. Additionally, dissolved oxygen did not appear to change during acute exposures up to 96 h, indicating that fog oil has a very low potential for creating a chemical oxygen demand, and there was no indication that increased microbial growth caused a biological oxygen demand in the static exposure results.

Scheier and Gominger (1976) studied the toxic effects of irradiated and non-irradiated water-soluble fractions of No. 2 fuel oil on five aquatic species. Of these five species, two were freshwater teleosts, the channel catfish (*Ictalurus punctatus*) and the bluegill sunfish (*Lepomis macrochirus*). The water-soluble fractions of the fuel oil was prepared in a water-to-oil ratio of 10:1. Mortality of *L. macrochirus* was 20% in 100% (v/v) of the non-irradiated water-soluble fractions; that of *I. punctatus* was 10%. The researchers did not quantify the amount of oil in the water-soluble fractions; therefore, actual exposure levels are not known.

Marine Organisms

Studies addressing the effects of fog oil on the marine environment are lacking. However, No. 2 fuel oil and diesel fuel have been identified as being chemically and toxicologically comparable to SGF-2 fog oil (Dauble et al. 1983; Shinn et al. 1985). These similar oils have been studied extensively and selected references are reviewed here.

Algae: Exposure of marine algae cultures to No. 2 fuel oil has both enhanced and inhibited growth rates (Dunstan et al. 1975). The volatile fraction of oil, which contains alkylbenzenes and toluenes, was the most biologically active. For the diatom *Skeletonema costatum*, 0.10 mg/L was toxic to growth in a tightly stoppered flask, and 1.0 mg/L was toxic when evaporation was allowed. For the green flagellate, *Dunaliella tertiolecta*, growth was enhanced in a tightly stoppered flask. When evaporation was allowed, no growth stimulation occurred. The enhancement of growth was attributed to increased permeability of the plasma membrane and nutrient availability.

Invertebrates: The effects of oil on marine invertebrates have been studied on annelids, mollusks, crustaceans, and coral.

Effects of the water-soluble fractions of No. 2 fuel oil on marine worms have been reported by Rossi et al. (1976). Two species of marine annelids, *Neanthes arenaceodentata* and *Capitella capitata*, were tested. The response of *N. arenaceodentata* was further broken down by age classes. The 24-h LC_{50} for both species and all age classes exceeded 8.7 mg/L of No. 2 fuel oil dissolved in water. The 96-h LC_{50} ranged from 2.3 to 2.7 mg/L for the two species; values for age classes of *N. arenaceodentata* ranged from 2.6 mg/L in 60-segment mature males to 8.4 mg/L in 4-segment juveniles. Controlled reduction of the oxygen levels did not affect toxicity of No. 2 fuel oil in the marine annelids.

Mollusks have been extensively studied because of their broad distribution and commercial value. Tarzwell (1971) exposed mature scallops to 12.5 mg/L No. 2 fuel oil and observed 100% mortality in a 24-h period. The embryonic and larval stages of mollusks are among the most sensitive to petroleum oils (Byrne 1989).

Eggs and larvae of the quahog clam (*Mercenaria*) were exposed to water-soluble fractions of No. 2 fuel oil by Byrne and Calder (1977). Oil was added to 27% saline saltwater in a gyratory shaker for 12 h. A period of 24 h was allowed for the solution to equilibrate, and the aqueous phase was then removed and used in concentrations ranging from 1% to 100%. The shellfish eggs experienced 50% mortality after 48 h of exposure to 0.43 mg/L. Two-day-old larvae exposed to solutions of No. 2 fuel oil experienced LC_{50} values of 1.3 and 0.53 mg/L after 2 and 10 days, respectively.

Byrne (1989) examined the cytokinetic effects from exposure to the water-soluble fraction of No. 2 fuel oil in the embryonic development of the quahog clam (*Mercenaria mercenaria*). The WSF was prepared with a gyratory shaker followed by equilibration for 24 h. The dissolved hydrocarbons were quantitated gravimetrically in the aqueous fraction. Test solutions were prepared in 10-ml aliquots containing 1% (0.23 mg/L), 5% (1.15 mg/L), 10% (2.3 mg/L), 25% (5.75 mg/L), 50% (11.5 mg/L), 100% (23 mg/L), and there were four untreated controls. Three hundred embryos were exposed to each concentration at 25°C. Normally, a free-swimming, straight-hinged larva should develop after the 48-h test period. In the control solutions, after 48 h, 297 of the 300 embryos had developed into free-swimming, straight-hinged larvae. In the test solutions containing the water-soluble fraction of No. 2 fuel oil more than 5 mg/L (ppm), 270 of the 300 embryos experienced cellular disruption within the first 3 h of exposure. At the end of the 48-h test period, 100% mortality occurred for water-soluble fraction concentrations of 5.75 mg/L or more. Percentage survivorship (± 95% confidence interval) in the less concentrated water-soluble fraction were as follows: 0.23 mg/L, 85% (± 4.9%); 1.15 mg/L, 34.5% (± 31.1%); and 2.3 mg/L, 8.5% (± 10%).

The nesting behavior, lipid content, and survival of the marine amphipod, *Amphitoe valida*, were studied during and after an acute exposure to the water-soluble fraction of No. 2 fuel oil (Lee et al. 1981). The exposure lasted 6 days and then the organisms were transferred to clean seawater for 7 days for subsequent observations. Twenty amphipods were added to the following duplicate dilutions of the water-soluble fraction of the fuel oil: 0% as a control and 5, 10, 15, 20, and 25%. The experiments were conducted at 20 °C. Lipids were extracted from the animal residues and weighed to determine total crude lipid content. Lipid content in control *A. valida* was about 2.8% dry weight and did not vary with age. The lipid content in exposed *A. valida* (5 to 25% WSF) ranged between 57.6 and 98.5% of the control value. Seven days after exposure, the lipid content of *A. valida* had declined further. These results imply that organisms exposed to water-soluble fraction solutions reduced their feeding and used their lipid reserves to survive. Mortality rates during the 6-day exposure period for all water-soluble fraction concentrations were low. Higher mortality was reported during the depuration phase at concentrations 15% and higher. The relationship between water-soluble fraction concentrations and mortality, however, was not linear; the 15% water-soluble fraction concentration produced the highest mortalities. Other investigators have also reported delayed mortality following exposure to sublethal levels of No. 2 fuel oil (Beck et al. 1983). Nest construction was adversely affected during exposure and depuration phases of the study. Persistence of impaired nest construction during the depuration phase indicates a potential reduction in recruitment rate in natural populations. The lower lipid content, nest construction, and survival were attributed to impairment or damage of the tactile sense for substratum chemoreception of food of mucus secretion for nesting, and mobility.

Atlas (1975) studied the effects of diesel fuel oil slicks on the amphipod *Boeckosimus affinis*. Oil-water mixtures containing 5 ml of oil were mixed with 5 L of water for exposure solutions. In some of the test containers, a nylon mesh screen was placed beneath the oil slick to prevent the organisms from physically entering the slick. The other test containers allowed the amphipods to enter the slick. The times required to kill 50% and 100% of the organisms were 13 days and 15 days, respectively. For amphipods with access to the slick, 1 and 2 days were required to attain 50 and 100% mortality, respectively.

The copepod *Tigriopus californicus* was exposed to mixtures of diesel fuel and saltwater and observed for 5 days (Barnett and Kontogiannis 1975). An ultrasonic probe and a magnetic stirrer were used for mixing. Separation of the mixture was noted 30 minutes after mixing. Complete mortality (n=25) was observed within 3, 4, and 5 days in dispersions of 1 mg/L, 0.5 ml/L and 0.25 ml/L, respectively. Dispersions of 0.10 ml/L caused 98% mortality after 7 days. However, mortality in the control group was approximately 50% after 7 days, compromising the interpretation of the data.

Survival, development, and growth were measured in the mud crab (*Rhithrapanopeus harrissii*) exposed in a static-renewal system to water-soluble fraction of No. 2 fuel oil over 6 months (Laughlin et al. 1978). Larvae were exposed to 2.5, 5, 10, 15, and 20% dilutions of the 6.3-mg/L water-soluble fraction. Measured exposure concentrations, however, ranged from 30 to 50% of nominal concentrations. Survival of the larvae was reduced in all dilutions after six months. The most pronounced impact was on the two highest exposures (15 and 20% water-soluble fraction concentrations); their respective percentages of survival were 37 and 6%. The mean duration of larval development to the megalopa stage increased significantly with increasing exposure levels. Subsequent developmental stages had no relationship with exposure concentrations, suggesting that the first larval stage is the most sensitive.

Sublethal effects of diesel fuel have been studied on four species of coral, *Porcillopora* cf. *damicornis*, *Povona gigantea*, *Psammocora* (*stephanaria*) *stellata*, and *Porites furcata* (Reimer 1975). After acclimation to the exposure chambers, 1 to 4 ml of diesel fuel was added and behavior was monitored. In all four species, mouth-opening responses were sustained much longer in the experimental groups than in the control groups. In two of the four species, no ingestion response was observed for as long as 17 days after exposure. Similar oil exposure tests have indicated delayed feeding responses in lobsters and barnacles (Atema and Stein 1974; Chipman and Galtsoff 1949; Smith 1968).

Vertebrates : Juvenile American shad (*Alosa sapidissima*) were exposed to oil-water mixtures of diesel fuel (Tagatz 1961). Known amounts of oil were added to a circulating aquarium. Dissolved oxygen levels were controlled and held above 6.0 mg/L. Total mortality occurred after 96 h of exposure at concentrations as low as 84 mg/L. In 24 and 48-h exposures, 50% mortality occurred at concentrations of 204 and 167 mg/L, respectively. Low dissolved oxygen concentrations increased the toxicity of diesel fuel to the exposed shad.

Dissolved oil was more toxic than whole-oil dispersions to three species of marine or estuarine fish: the sheephead minnow (*Cyprinodon variegatus*), silversides (*Minedia beryllina*), and *Fundulus similus* (Anderson et al. 1974). The most tolerant species was *C. variegatus*, with 24-h LC_{50} values of 250 and >6.9 mg/L for a whole-oil dispersion and the water-soluble fraction, respectively. The most sensitive of the three species was *F. similus*, which had a 24-h LC_{50} of 48 mg/L for whole-oil dispersions and 5.6 mg/L of the water-soluble fraction. The fraction of dissolved No. 2 fuel oil in the artificial seawater was 8.7 mg/L after 20 h.

Linden et al. (1979) described the combined chronic effects of salinity, temperature, and exposure to sublethal levels of water-soluble fraction of No. 2 fuel oil on the estuarine killifish, *Fundulus heteroclitus*. Killifish embryos were exposed at three salinities (10, 20, and 30%) and three temperatures (20, 25, and 30°C) to three water-soluble fraction dilutions (15, 20, 25%) and a control. The three water-soluble fraction concentrations were noted to equal approximately 0.28, 0.38, and 0.47 mg/L total naphthalenes. The 10% dilution was mildly toxic to embryos at optimal salinity and temperature (20% salinity, 23°C), while the 25% dilution was very toxic in all combinations of temperature and salinity. More than 50% mortality occurred even under optimal conditions for the 25% dilution. Salinity mildly affected the animals' development rate, but temperature markedly affected development. Interaction of temperature and salinity with exposure to No. 2 fuel oil inhibited normal development.

4.4.3 Transformation

Transformation of fog oils and surrogate oils in soil and aquatic habitats involves both microbial degradation and photolytic (photooxidation) processes. Photolysis of petroleum products can produce compounds that have greater toxicity than the original hydrocarbon constituents. Aquatic microbial degradation of petroleum has been extensively examined; however, there is little information regarding the degradation of fog oils.

Biotransformation of oils by microorganisms can affect the persistence, mobility, and toxicity of oils. Soil biotransformation is addressed here because oil deposited on vegetation and soil may be washed into aquatic habitats. Factors affecting this pathway include soil properties, ground- water level and gradient, rainfall, temperature, and other meteorological conditions (Liss-Suter and Villaume 1978).

Soil Biotransformation

Raymond et al. (1976) studied the biotransformation of No. 2. fuel oil in three soil types, Pennsylvania Glenville silt loam (pH 5.4), Oklahoma sandy loam (pH 6.3), and Texas black clay loam (pH 7.6). The oil was poured on 1.7- x 3.0-m plots of each soil type in 2.5-kg/m^3 amounts and was readily absorbed. The soil was aerated by tilling the top 15 cm in each plot. During the winter months, little transformation was noted. Application of fertilizer did not significantly stimulate transformation. After 1 year, the average oil reduction in the soils ranged from 48.5% to 90%. Silica gel fractionation of oil extracted from the soil indicated that transformation was selective. The more polar hydrocarbons degraded more slowly than those with less polarity. Transformation rates did not exceed 500 g/m^2 per month. No significant differences between soil types were noted and microflora colonies increased greatly after oil application. Microflora exposed to oil developed a black pigment. The hydrocarbon-utilizing microflora were primarily fungi and the aerobic *Nocardia* species.

Aquatic Biotransformation

Biotransformation of oils mainly results from microbial activity in water and sediments (Atlas 1981; Liss-Suter and Villaume 1978; Koerting-Walker and Buck 1989; Blumer et al. 1970). Petroleum biodegradation has been observed in marsh sediments to a depth of 60 cm below the sediment-water interface (Blumer and Sass 1972).

Koerting-Walker and Buck (1989) examined the potential petroleum-degrading ability of bacteria using a 40-day shaker flask test. A culture medium composed of artificial seawater and trace metals was inoculated with a mixed bacterial suspension derived from marine sediment, and No. 2 fuel oil was added to monitor oil degradation with time. The fuel oil/culture-medium solution without the bacterial inoculum was used as the control to measure oil concentrations over time in the absence of bacteria. In both treatments, the aromatic oil concentration decreased significantly over time. Comparison of oil loss for both treatments indicated that bacterial degradation was not significant. Although the bacteria population increased over the 40-day period in the inoculated test solution, the removal of aromatics was attributed to evaporation. Researchers evaluated only aromatic concentrations, but it is possible that the aliphatic constituents may have been selectively used by the bacteria. The researchers noted that such selective degradation would be consistant with the fact that these species of bacteria require organic rather than inorganic carbon.

The rate of biodegradation may be influenced by other aquatic animals. For example, bioturbation of sediment by the tube worm *Clymenella torquata* enhanced microbial growth (Koerting-Walker and Buck 1989). Gardner et al. (1979) observed enhanced microbial degradation PAHs in the upper sediment as a result of *Capitella capitata* activity. Bauer et al. (1988, cited by Koerting-Walker and Buck 1989) also observed increased microbial degradation as a result of bioturbation by benthic organisms. Bioturbation by the tube worm *C. torquata* influenced the removal of No. 2 fuel oil from sediment and enhanced bacterial colonization (Koerting-Walker and Buck 1989). This tube worm has a wide distribution and unique feeding behavior, and it predominates during late stage succession following sea floor disturbances (Yingst and Roads 1980; Roads and Boyer 1982). *C. torquata* ingests sediment from the bottom of its tube, 15 to 20 cm below the sediment-water interface, and defecates directly into the water column. Additionally, *C. torquata* collects surface sediment in a hoeing action for ingestion or tube construction (Dobbs 1981; Dobbs and Whitlatch 1982).

To determine the effect of one worm on the distribution of oil on its immediate environment, changes of oil concentrations over time were monitored in oiled sediment, oiled sediment plus a worm, and stratified oiled sediment to which a worm was added (Koerting-Walker and Buck 1989). All treatments were conducted under three temperature regimes (4.5°C in March, 7.5°C in April, and 21°C in July-August) to evaluate any seasonal differences associated with oil degradation. The burrowing and feeding behavior of *C. torquata* had a significant effect on the removal of oil from the sediment. The proportion of the two-ring aromatics remained about the same in both treatments indicating that the oil constituents were not selectively removed nor microbially degraded. Temperature/season differences did not account for increased worm activity, but did account for a physical effect on the solubility of lightweight aromatics. The presence of *C. torquata* for the March and July treatments showed significant oil removal, as compared to treatments in those months without the animal, but no difference was observed in April. The differences in oil concentration between spring and summer was significant ($p < 0.01$). Removal was greatest in July.

4.4.4 Photolysis

Photolytic reactions caused by exposure to sunlight may increase the soluble fraction and the toxicity of hydrocarbons in oils. Ultraviolet light is responsible for the formation of free radicals and subsequent oxidation reactions involving oil constituents. Larson et al. (1977) simulated and characterized an environmental exposure of No. 2 fuel oil to ultraviolet radiation. The No. 2 fuel oil was 77% C-10 to C-22 n-aylkalenes and other saturates and 23% aromatic hydrocarbons. Irradiation of the oil for 24 h simulated a bright sunny day at 40° N latitude, with the oil temperatures ranging from 21 to 23°C. A second oil tray was kept dark for a control.

After 12 h of irradiation, the oil had become visibly turbid, a condition that continued for 3 days, after which a fine particulate material settled on the bottom. The fine particulate was highly oxidized organic compounds and contained alcohols, carbonyl compounds, and carboxylic acids. Peroxide increased at a linear rate for 90 h and the phenolic compounds increased linearly for 165 h. The carbonyl compounds were largely derived from the benzylic hydrocarbons. The control oil tray did not change in its turbidity and acidity, nor did the content of peroxides, phenols, or total carbonyl compounds. The same chemical changes have been documented with irradiated vaporized and bulk fog oil, with minor differences (Poston et al. 1988)

Poston et al. (1986) compared the effects of photolysis of vaporized and bulk SGF-2 fog oil on toxicity and chemical composition. In 48-h acute exposures of *H. azteca*, there was no difference between vaporized and bulk oil in toxicity. The 48-h LC$_{50}$ was about 11.5 mg total oil/L for photooxidized fog oils. Photooxidized vaporized and bulk fog oil were more toxic than the unexposed fog oil. Photolysis was responsible for the production of polar materials that acted as emulsifiers and resulted in higher concentrations of water-soluble constituents in the irradiated oils. Additionally, photolysis resulted in the production of such chemicals as aromatic ketones that have toxic properties distinct from those of the original bulk oil.

Scheier and Gominger (1976) investigated the effects of irradiation on the toxicity of water-soluble fraction of No. 2 fuel oil to five species of fish. The water-soluble fraction of the fuel oil was prepared in a water-to-oil ratio of 10:1. The amount of oil in the water-soluble fraction was not measured; consequently, actual exposure levels are not known. After mixing was completed, the water-soluble portion was removed and split into two glass test containers. One container was then exposed to continuous light from a 275-watt sunlamp. The LC$_{50}$ concentration for *I. punctatus* exposed to the irradiated solution was 75% v/v (± 3.8% @ 95% C.I.) of the water-soluble fraction, whereas in the non-irradiated solution, 90% survival occurred in 100% v/v water-soluble fraction by volume. The *L. macrochirus* was more sensitive to both solutions. The group exposed to the irradiated solution had a LC_{50} of 39.6% v/v (± 2.8% @ 95% C.I.) of the water-soluble fraction, and for the group exposed to the non-irradiated solution, 80% survival occurred in 100% water-soluble fraction, by volume.

A transformation toxicity test was performed on grass shrimp *Palaemonetes pugio* under a relatively accurate simulation of natural estuarine conditions (Scheier and Gominger 1976). The preparation process included floating 1 L of No. 2 fuel oil over 360 L of brackish water replenished at 3 L/h. Two sunlamps provided ultraviolet irradiation for water solutions exposed for 24 h, 72 h, and 6 days. A chemical comparison between vat water exposed to ultraviolet irradiation for 6 days and vat water that was not exposed to ultraviolet irradiation for 6 days revealed that the ultraviolet exposure promoted increases of 0.52, 2.35, and 2.9 mg/L in phenols, aromatic hydrocarbons, and aliphatic hydrocarbons, respectively. Concentrations in 6-day-old non-ultraviolet exposed oil-water mixtures were 0.23, 0.35, and 1.4 mg/L, respectively. Increased mortality was attributable to the increase in soluble, photochemically generated constituents in the seawater.

4.4.5 Bioaccumulation

No information on the uptake and accumulation of fog oils by freshwater or marine organisms was found in the literature; however, some data address accumulation of organic constituents of fuel oil. In most studies, bioaccumulation factors have not been reported because of highly variable exposure concentrations. Liss-Suter and Villaume (1978) reviewed several studies addressing bioaccumulation of No. 2 fuel oil constituents. Green algae, filter-feeding mollusks, fish, and herring gulls accumulated hydrocarbons from an oil spill in Buzzards Bay. The oil persisted for up to a year in the shellfish. Marine annelids have shown the ability to concentrate substituted benzene, naphthalene, alkylated naphthalene, aromatic hydrocarbons, and paraffins for fuel-oil-contaminated water. There is also evidence that freshwater fish can accumulate hydrocarbons, tainting the flavor of the flesh. This evidence was supported in part by column and gas chromatography and ultaviolet and fluorescence spectroscopy.

4.5 MITIGATION

Fog oil droplets are inhalable, and surface deposits can accumulate in terrestrial and aquatic systems as a result of research and development and performance testing. In some instances, mitigation is recommended.

Mitigation approaches that involve reducing the amount of material disseminated during tests by reducing dispersion rates, the number of tests per site, altering the physical characteristics of the material, or the use of new (replacement) materials involve considerations of research and development and performance and are beyond the scope of this review. The mitigation approaches considered here are limited to activities that may reduce the impact on health and the environment of fog oil aerosols as they are currently disseminated.

When possible, research and development and performance tests involving fog oil aerosols should be performed in wind tunnels (such as the Breeze wind tunnel in Edgewood, Maryland) or in other facilities having particle filtration capabilities. The Breeze tunnel can be used to test full-scale systems; however, its ability to handle full-scale fog oil releases is not known. Other wind tunnels are available to test reduced-scale dissemination systems for environmental deposition, resuspension, fate, and effects, and for bioavailability and toxicity to animals.

4.5.1 Human Health

Because fog oil smokes are largely respirable, and because data suggest an occupational risk for workers after acute or repeated exposures to oil mists, the inhalation of mixed fog oil aerosols should be limited. Respiratory protection should be provided to personnel during plume dispersion. Eye protection should also be provided to reduce the risk of eye irritation. Frequent washing of skin and clothing will minimize the potential for acute and chronic adverse dermal effects, and protective gloves, hats, and other garments should be provided to reduce the amount of oil contact with the skin. Prior to smoke-generation tests, personnel should be screened for chronic skin disease, organic diseases of the lungs, heart, kidneys or liver, and history of allergy to hydrocarbons. In addition, fog oil stocks should be tested prior use to ensure that they are carcinogen-free (Palmer 1990).

4.5.2 Terrestrial Systems

A key factor in mitigating the effects of fog oil aerosols in terrestrial systems concerns the timing of testing activities. Oil effects in plants are less severe in the absence of actively growing foliage (Clark and Finley 1977; Ilandgovan and Vivekanandan 1989), and timing of generation tests relative to growing seasons may reduce adverse impact on plant communities. As discussed in Section 4.3, abiotic factors such as temperature greatly affect the volatilization and fate of fog oil aerosols. Temperature also affects biodegradation rates of hydrocarbon materials. Thus, if tests can be conducted during spring and summer months in most climatic regions, impacts of fog oil aerosols on vegetation might be reduced and the persistence of hydrocarbons in the soils might be decreased. This approach may be less viable in arid and semiarid climatic regions. In those ecosystems, impacts may be lessened if testing is conducted during early spring months when temperatures are rising, but when water stress is less than during summer months.

Some evidence (Warner et al. 1984) indicates that impacts from hydrocarbon contaminants (diesel fuel) on plants are greater if the contaminants are mixed into the soil profile and readily available to the entire root system for absorption. Warner et al. (1984) found that barley growing in soils that were amended with diesel fuels showed greater toxic responses than plants growing in soils where fog oils were deposited either on the surface or in a subsurface layer. Thus, mitigation approaches that involve plowing or mixing of soils to distribute the hydrocarbons may not minimize impacts to terrestrial vegetation, but may in fact increase them.

Separating applications by several hours or days (depending on ambient temperature) will also greatly reduce the potential risk to terrestrial systems by allowing evaporative loss and preventing fog oil accumulation. When test objectives permit, deposition to soil and plants may also be minimized by reducing smoke down-wash. Down-wash can be reduced by raising the ejector to a more vertical position or ejecting the aerosol at an angle to the mean wind direction. Reduced smoke deposits will reduce potential exposure of wild animals to toxic levels of fog oil. In addition, mitigation of wildlife impacts may best be accomplished by avoidance of areas where sensitive animals (e.g., waterfowl) or endangered species may be exposed to the smoke by inhalation, ingestion, or dermal deposition. The sensitivity of some wildlife species to human disturbance (Klein 1976) may help limit the number that would be exposed to the high airborne levels of fog oil that occur near the generators and the mobile course. If harmful levels are expected in areas to which wildlife have retreated, noise generators could be used at more distant locations. If a protected species occurs on the selected site, compliance with the Endangered Species Act of 1973, as amended, must be ensured and the project modified, if necessary, to prevent jeopardy to the protected species.

Limiting excessive use of the road courses by heavy equipment will greatly reduce potential ozone production in association with the generation tests. Tests should not coincide with large-scale maneuvers when air stability is high.

4.5.3 Aquatic Systems

Fog oils have the potential to accumulate in the aquatic environment if they are being routinely used, and they could reach acutely toxic levels for some benthic organisms. However, after cessation of the use of fog oils, biological and, to some degree, chemical degradation of fog oil constituents is likely. Over a protracted length of time, conditions would likely revert to normal for a particular habitat. However, the time frame for these processes could be on the order of years. Therefore, fog oil aerosol should not be generated in areas where deposition of the smoke in aquatic systems will result. Generating the smoke at high ambient temperatures will reduce the deposit and run-off to water surfaces. Generation when daylight periods are long may accelerate photolytic degradation of oil constituents and facilitate biodegradation by increasing the aqueous solubility of fog oil constituents. However, this possibility must be weighed against the resulting increase in toxicity of the photooxidized oil. Containment and cleanup procedures designed for oil spills in waterways are somewhat effective in mitigating aquatic effects and may decrease impacts on aquatic wildlife as well. It is not known how effective these measures will be on oil-coated particulates, such as graphite.

4.6 ENVIRONMENTAL IMPACTS OF RESEARCH AND DEVELOPMENT, MANUFACTURE, TRANSPORTATION, STORAGE, AND DISPOSAL

Safety issues are typically addressed in specific test plans and are not covered by this review. Personnel safety is the responsibility of the test site safety officer. The following sections address the general issues related to health and environmental impacts of fog oil or other lubricating oils.

4.6.1 Environmental Impacts of Research and Development

The environmental dissemination of fog oil results in two types of contamination. The first is the relatively large surface area of soil or water on which dispersed oil is deposited. Even under worst-case conditions, surface deposits are estimated to be less than 10 mg/m^2 at all distances greater than 2 km from the source. At these levels, terrestrial and aquatic risks from fog oil exposure are minimal. Airborne concentrations more than 2 km from the generator are also harmless to humans and wildlife. For the second type, the higher accumulations of oil that occur around generators or point sources (0.05 to 1.5 g/m^2), physical removal is recommended. However, mechanical clean-up methods are inadvisable in areas where ground disturbance will result in erosion [e.g., at arctic and subarctic test sites where permafrost degradation may occur (Hunt et al. 1973)] or increase incorporation into the soil during the plant-growing season.

Personnel protection is recommended for individuals within the airborne fog oil clouds. At a minimum, this should include full-face particle masks for respiratory protection and prevention of eye irritation. Skin should be protected from exposure and appropriate hygiene measures followed to remove oil deposits from skin and clothing. Respiratory exposure to airborne fog oil may also be harmful to other vertebrate species, particularly small mammals and birds. Because the population stability of species with critically low populations (endangered species) can be aversely affected by a small increase in mortality, generation of smoke where such species are present should be avoided. Also, whole populations of animals may be impacted by respiratory exposures to airborne fog oil when the animals are concentrated within a small area. Dispersion of fog oil should be avoided in areas or at times when migrant species are congregating in high-risk-exposure areas.

4.6.2 Manufacture and Transportation

Fog oil has a flash point of 320 °F and is therefore not a flammable or combustible liquid under the U.S. Department of Transportation's hazardous materials transportation regulations (49 CFR 173.120). However, cyclohexane is classified as a flammable liquid and petroleum is classified as a flammable liquid (40 CFR 172), making these materials subject to the labeling, packaging, and transportation requirements of the HMTA.

4.6.3 Storage

Storage of unused fog oil is subject to the regulations relating to federal employee occupational safety (29 CFR 1960). Fog oil is not subject to the reporting requirements from releases of hazardous substances in 40 CFR 302, although release of fog oil on waters of the United States may be subject to Clean Water Act requirements in Section 311(b)(1).

4.6.4 Disposal

Fog oil is not listed as a hazardous waste under RCRA.

5. CONCLUSIONS

Evaluations based on modeled estimates and scientific studies of the environmental and toxicological impacts of the fog oil smoke plumes are summarized in this section. Where data are insufficient to permit summary conclusions, or where additional data would serve useful purposes in expanding the environmental assessment of fog oil aerosols, data needs are identified.

5.1 ENVIRONMENTAL AND TOXICOLOGICAL IMPACTS

The environmental toxicity, human health risk, and effects of fog oil aerosols on terrestrial and aquatic systems are summarized in relation to the predicted dissemination and deposition of the aerosols and resultant exposures in downwind environmental compartments.

5.1.1 Environmental Dissemination and Deposition

Potential impacts from the dissemination of fog oil depend on either air concentrations (in the case of human inhalation or dermal exposure) or the mass loading of ground, vegetative, and aquatic surfaces (in the case of environmental impacts). Fog oil aerosols are dispersed by vaporization and condensation methods, and windborne droplets are similar in composition to the bulk material. Periods of generation generally range between 10 and 30 min; however, long-term and large-area use of the material as an obscurant smoke is accomplished using multiple or sequential generators. The aerodynamic size of fog oil droplets range between about 0.6 and 3 μm, with settling velocities between roughly 0.001 and 0.03 cm/s. These aerodynamic characteristics strongly influence the dispersion, deposition, and inhalation potential of fog oil smoke.

Downwind air concentrations and surface deposits were estimated by assuming certain operating and atmospheric conditions. The model used in Appendix A may be sufficient for most applications; however, more sophisticated models or actual field measurements may also be employed during fog oil tests or trials to identify the source term related to health and environmental impacts. Estimates of fog oil air concentration, for a single 30-min XM56 test, generally decrease from between 7 and 140 mg/m^3 at downwind distances between about 0.1 and 0.2 km, to between 0.003 and 0.3 mg/m^3 at a distance of 40 km. Potentially harmful air concentrations of fog oil ($\geq$10 mg/m^3) are predicted to occur within 0.4 to 2 km of the source, depending on atmospheric conditions. The predicted impact of these concentrations was to potentially degrade visibility within 0 to 25 km of the source; actual light transmittances would depend greatly on atmospheric conditions. Estimates of surface deposition range from 30 to 800 mg/m^2 at a distance of 1 km downwind of the source to less than 0.001 to 0.3 mg/m^2 at a distance 40 km downwind. Even under worst-case atmospheric conditions, fog oil deposition was estimated to be less than 10 mg/m^2 at downwind distances greater than about 2 km from the source. Resuspension or redistribution of fog oil is likely to be limited to areas susceptible to soil erosion and flowing streams.

5.1.2 Material Toxicity

With appropriate respiratory and skin protection, SGF-2 poses little to no toxic threat to human health during typical test and training exposures. Only "new" fog oil obtained under MIL-F-12070C, Amendment 2 specifications should be used for testing and training exercises and these stocks should be tested to ensure that all carcinogens have been removed. Fog oil is moderately harmful, either chemically or physically, to terrestrial plants and animals and can accumulate in food chains, providing a vehicle for uptake of other oil-soluble xenobiotics. However, the area of impact under typical testing and training scenarios would be small and no population/community structure changes are anticipated. Because of differences in volatilization, deposition, and biotic response under extreme climatic conditions, desert and arctic environments may be more sensitive to fog oil releases than predicted for temperate zones. Aquatic systems appear to be the most vulnerable to fog oil toxicity, and SGF-2 deposition on aquatic systems should be avoided.

5.1.3 Human Health Risk

Fog oil concentrations in most of the plume area are not expected to reach the levels that have been shown to cause an adverse pulmonary response from either acute or subchronic exposure. However, hazardous levels may be present up to 2 km of the source, depending on environmental conditions. Under all conditions, personnel within about 0.1 km of the generators may be exposed to concentrations above the STEL of 10 mg/m^3. In the ACGIH 1992-1993 threshold limit values documentation (ACGIH 1992), the notice of intended changes for mineral oil mist recommends deleting the STEL and changes the TWA for mildly refined oil mists that contain polycyclic aromatic hydrocarbons (PAHs) to 0.2 mg/m^3. Only minor impacts to respiratory structure and function occur following repeated exposures to $\geq$ 500 mg/m^3 fog oil (alone or co-generated with graphite flake) at frequencies and for durations much greater than those encountered during typical production prove-out tests. As recommended by the Surgeon General, respiratory protection should be used when ever cloud density decreases visibility to 50 feet. Generally, there are more effects in rats exposed to aerosol mixtures of fog oil and graphite than to fog oil aerosols alone.

Carcinogenic compounds are found in some fog oil stocks; however, the potential risk of pulmonary or skin cancer from SGF-2 exposure is reduced but not always eliminated under current military procurement requirements for refined fog oils. Additional requirements for carcinogen testing of stock fog oils would eliminate the tumorogenic potential of fog oil exposure. Recommendations by Palmer (1990) include a proposed amendment to the military specification for fog oils to include a requirement for tests demonstrating the absence of carcinogens. Furthermore, Palmer recommends the following: (1) at a minimum, mutagenicity data, as determined by the modified Ames assay of Blackburn (1984) or PAH content, as determined by the FDA analytical test for white oil purity (Falk et al. 1964), should be provided by the manufacturer. (2) Stockpiles of conventionally-refined oils purchased before the Military Specification was amended to exclude carcinogens should no longer be used for production of smokes to which military personnel are exposed. (3) The current inventory of fog oil purchased after the specifications were revised in April 1986 should be examined to ensure that all batches are carcinogen-free. For this purpose, the FDA test for white oil purity (Falk et al. 1964) should suffice. (4) An 8-hr TWA exposure limit of 5 mg/m^3 (for the respirable fraction) should be adopted for "new" fog oil. While some masking may be necessary with this exposure limit, in most situations the majority of soldiers will not be exposed to oil concentrations greater than 5 mg/m^3. (5) Repeated-dose toxicity studies should be conducted to obtain data on the effects of exposure to fog oil mist concentrations between 5 and 63 mg/m^3. The effects in mice or rats should be compared to those in monkeys. (6) Studies should be conducted to determine whether the development of pulmonary disorders can be exacerbated by the presence of additives or contaminants in mineral oils.

Although SGF-2 is a moderate skin irritant, the risk of skin conditions from prolonged exposure to oils can be reduced by attention to worker personal hygiene. SGF-2 may be weakly mutagenic but does not appear to pose an acute genetic risk. The most serious consequences of oil exposure result from aspiration of ingested oil, but exposure by this route is unlikely. Induction of the cytochrome P450 system may increase/decrease xenobiotic metabolism in exposed individuals. There is little risk of deflagration or explosion of fog oil or mixed fog oil/graphite flake smokes. However, visibility is diminished in and through the plume, and hazardous driving conditions may develop in areas of public access.

5.1.4 Terrestrial Impacts

The potential risks from recurrent use of fog oil aerosols as obscurants are believed to be moderate, and effects are not expected to persist in the environment. The major portion of discernible effects would be expected to occur within a 0.1-km radius of the point of generation of the fog oil aerosols. Moderate phytotoxic effects are observed in a variety of plants exposed to fog oils, and none of the species appear to acclimate to or compensate for repeated oil exposure. Although biomass production is decreased in some species, seed germination is not affected. Soil invertebrate and microbial components do not appear to be adversely affected by fog oil exposure; however, changes would be expected in the species composition of the soil microbial community. Impacts at the community level resulting from increased populations of those microbial species that are capable of utilizing fog oil hydrocarbons are not known. Wildlife inhabiting areas near the source may encounter levels of fog oil that cause adverse health effects or reproductive dysfunction in wild animals. The contaminated area would be relatively small and no population impacts are expected unless congregations of animals or sensitive endangered species are exposed. Because the effects of fog oil aerosols in birds are extrapolated from mammalian data, and because birds are generally much more sensitive to airborne pollutants than mammals, the impact of fog oil smokes on wild birds may be underestimated in this evaluation. Waterfowl casualties are high in water systems contaminated with oil slicks.

Although the low mass-loading rates and the high rates of volatilization of fog oil from soil and plant surfaces will minimize toxic effects to most terrestrial systems, extreme environments, such as those used for desert and arctic weather performance tests, may be more sensitive to fog oil releases. For example, plant damage is greater under desert conditions of high temperature and low humidity. Extreme cold can greatly reduce volatilization of fog oil, and deposited oil can be redeposited on sensitive growing plants or into aquatic systems during the summer melt cycle. Fog oil can also be resuspended on blowing snow and accumulate in drift areas that may be critical habitats for wildlife reproduction or migration.

5.1.5 Aquatic Impacts

There is limited data on the effects of fog oil to aquatic organisms. Because of the chemical and physical similarities between fog oils, diesel oil, and No. 2 fuel oil, environmental data for the latter two can be used to estimate the effects of SGF-2 on aquatic systems. In particular, emphasis was placed on data from studies using No. 2 fuel oil, which has also been identified as being toxicologically similar to SGF-2 fog oil.

Both chemical toxicity and physical impairment caused by fog oil contribute to mortality in toxicity tests. The relative significance of each, however, depends on the species tested and the methodology. In the field, little direct chemical impact to aquatic organisms is anticipated after a single 30-min generation of fog oil smoke. However, deposition of fog oil from a 30-min generation onto a 1-m deep body of water near the source will result in oil concentrations that are physically detrimental to aquatic invertebrates. Multiple smoke generations are likely to result in significant reduction in algal growth and in mortality of aquatic organisms. Particular animals, such as filter-feeding and benthic organisms, may be at greater risk due to their increased exposure to either suspended microdroplets or oil-impacted sediment. Although short-term episodic releases of fog oil on its own are not acutely toxic, aquatic life can be adversely affected if concentrations reach levels in excess of the fog oil's true solubility. Several physical and chemical mechanisms act to selectively fractionate or disperse individual constituents of the oil in water systems. The soluble fraction of SGF-2 is largely low-molecular-weight aromatic hydrocarbons, which are acutely toxic to aquatic organisms. The insoluble constituents have been shown to inhibit such functions as chemotaxis or feeding in benthic organisms. Toxicity to aquatic life for both marine and freshwater systems can be exacerbated by irradiation with sunlight, resulting in photolytic reactions primarily attributable to the ultraviolet spectrum. Oil constituents are known to accumulate in aquatic organisms; however, chronic exposures are not well documented and long-term effects have been inferred from studies with No. 2 fuel oil. Biological and chemical degradation of fog oil constituents is likely to occur, but the processes may take many months to complete. Also, a surface film or slick may form and impose physical stresses on aquatic organisms. To avoid these chemical and physical impacts, fog oil aerosol should not be generated in areas where deposition of the smoke on aquatic systems will result.

5.2 DATA NEEDS

The data related to the environmental fate and toxicological effects of fog oil aerosols are not complete. Research tasks are identified here that would provide additional information to aid the environmental assessment of the military use of the material. In addition, less is known about the environmental fate and toxicological effects of mixed fog oil and graphite flake aerosols. Conclusions may be inferred from data available for graphite-only and fog oil-only materials. However, research tasks are identified here from which information on the impact of the combined materials would aid continued environmental assessment of the military use of the mixed obscurants.

5.2.1 Aerodynamic Characteristics and Plume Dispersion

The aerodynamic characteristics of individual fog oil droplets are well understood. In addition, the characteristics of windborne fog oil plumes do not pose any unusual difficulties in estimating air concentrations. However, data on the rates of fog oil smoke deposition on typical surfaces are limited to wind-tunnel studies. Field measurements have resulted in undetectable fog oil residues. This failure may be caused by difficulties in analyzing fog oil residues or by reflection of fog oil plumes from surfaces. Additional wind tunnel studies could provide more information on fog oil deposition rates to various surfaces and in the presence of graphite flake aerosols (the XM56 produces both types of obscurants). The possibility of performing controlled field experiments should also be studied to determine whether or not useful surface deposition information could be obtained.

5.2.2 Fog Oil Fate in the Environment

It is known that fog oil degrades in the environment. To investigate the processes and rates of degradation, studies should be performed under natural or simulated field conditions. The degradative processes may include evaporation and chemical, photochemical, and microbial degradation. The studies should include soil, plant, and water surfaces. Rates of degradation under typical field conditions would aid site-specific environmental assessments.

5.2.3 Human Health Risk

Current exposure limits for fog oil are based on data from rodent studies, yet primates appear to be considerably more vulnerable to respiratory impacts of oil mists than laboratory rodents. More study is needed to determine the best animal model for human fog oil toxicity. Data are also needed on the effects of chronic fog oil exposure that more directly characterize career exposures of military personnel [e.g., 6 h per week for an average of 6 years (Palmer 1990)]. Because inhaled, aspirated, ingested, and dermally absorbed oils are distributed to many organs, the distribution and effects of subchronic SGF-2 exposure on organ function should be investigated. Additionally, information on the effects of SGF-2 on central nervous function, behavior, reproduction, fertility, and teratogenesis is also lacking.

5.2.4 Bioavailability and Toxicity of Fog Oil Aerosols in Terrestrial Systems

Information is lacking concerning the impacts of fog oil and mixed fog oil/graphite aerosols on above-ground insect populations. Although the impacts to vegetation and insects are expected to be limited to the area surrounding the generation source, a screening study to determine the mass-loading rates at which insects begin to experience negative impacts would be helpful.

No information is available to adequately assess the effects of repeated exposures to fog oil and fog oil/graphite flake aerosols on native vegetation. No information is available concerning the possible changes in plant community structure induced by repeated fog oil or mixed aerosol exposures or the impacts of repeated exposure of plants in stressed conditions (e.g., vegetation in arid or semiarid areas that experience water stress for much of the year).

Potential wildlife impacts can, in part, be inferred from laboratory data gathered on lubricating oils and field studies in the aftermath of oil spills. However, the effects of different types of petroleum hydrocarbons on the health of wild animals can vary from no effects to significant reproductive reduction. More direct information on the response of wild mammals, birds, and reptiles to SGF-2 exposure are needed. The information needed includes dose-response data on respiratory toxicity of fog oil and mixed fog oil/flake aerosols in birds; pathological and reproductive impacts of ingested fog oil and mixed aerosols in birds, reptiles, and wild mammals; and the effect of fog oil deposition on hatchability of bird eggs.

5.2.5 Bioavailability and Toxicity of Fog Oil Aerosols in Aquatic Systems

There is limited information about the effects of SGF-2 on freshwater organisms. Most of the available information comes from only a few studies. Because fog oil has such limited solubility, additional testing should be directed towards evaluating sub-lethal effects of SGF-2 on freshwater organisms, in particular sediment toxicity, effects on reproductive success and behavior, and embryo larval toxicity of different aquatic organisms. To the extent that it is determined that fog oil may be introduced into marine or estuarine habitats, additional testing should be done to corroborate the conclusions extrapolated from studies on diesel and fuel oil in marine systems. The emphasis should be on sub-acute effects. Of particular importance is the potential impact of fog oil exposure on the recruitment of salmonid species to original stream beads.

5.2.6 Mitigation Approaches

Mitigation approaches that involve reducing the amount of material disseminated during tests by reducing dispersion rates, the number of tests per site, altering the physical characteristics of the material, or the use of new (replacement) materials are beyond the scope of this review. The mitigation approaches discussed are limited to activities that may reduce the impact on health and the environment of mixed fog oil/flake aerosols as they are currently disseminated.

When possible, research and development and performance tests involving fog oil and mixed fog oil/flake obscurant aerosols should be performed in wind tunnels (such as the Breeze wind tunnel in Edgewood, Maryland) or in other facilities having particle-filtration capabilities. The Breeze tunnel can be used to test full-scale flake systems; however, its capability to test full-scale fog oil release is not known. Other wind tunnels are available to test reduced-scale dissemination systems for environmental deposition, resuspension, fate, and effects, and for bioavailability and toxicity to animals. When possible, procedures that reduce down-wash of smoke to the surface should be instigated to reduce graphite and fog oil deposition to soil and plants. Avoidance of areas or periods when sensitive or protected species are within 2 km of the source will minimize impact of smoke generations on wild life populations. Deposition to water systems should be avoided. Personnel potentially exposed to the smoke should be equipped with and use safety equipment to reduce respiratory, ocular, and dermal exposure.

Blank

6. LITERATURE CITED

ACGIH. 1985. Particle Size-Selective Sampling in the Workplace: Report of the ACGIH Technical Committee on Air Sampling Procedures. American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio.

ACGIH. 1986. Documentation of the Threshold Limit Values and Biological Exposure Indices, 5th ed. American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio.

ACGIH. 1992. Documentation of the Threshold Limit Values and Biological Exposure Indices, 6th ed. American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio.

Albers, P. H. 1976. "Effects of External Applications of Oil on Hatchability of Mallard Eggs." In Proceedings of Symposium on Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms, ed. D. Wolfe. Pergamon Press, New York.

Anderson, J. W., J. M. Neff, B. A. Cox, H. E. Tatem, and G. M. Hightower. 1974. "Characteristics of Dispersions and Water-Soluble Extracts of Crude and Refined Oils and Their Toxicity to Estuarine Crustaceans and Fish." Marine Biology 27:75-88.

Aranyi, C., N. Rajendran, S. C. Vana, J. N.Bradof, J. G. Drummond, R. L. Sherwood, M. J. Tomlinson, J. S. Tepper, B. S. Levine, R. D. Gibbons, and J. C. Dacre. 1992. "Inhalation Exposure of Laboratory Rats to Aerosol Mixtures of Fog Oil and Graphite for Use as Military Obscurants." In Proceedings of the Smoke/Obscurants Symposium XVI. Science and Technology Corporation, Hampton, Virginia.

Ashkenazi, A. E. and S. E. 1961. "Experimental Keroxene Poisoning in Rats: A Report Based on Fourteen Cases." Jpn. J. Ind. Health 13:507-513.

Atema, J. and L. Stein. 1974. "Effects of Crude Oil on the Feeding Behavior of the Lobster, *Homarus americanus*." Environ. Pollut. 67:77-86.

Atlas, R. M. 1975. Fate and Effects of Oil Pollutants in Extremely Cold Marine Environment. AD A018711, Office of Naval Research.

Atlas, R. M. 1981. "Microbial Degradation of Petroleum Hydrocarbons: An Environmental Perspective." Microbiol. Rev. 45(1):180-209.

Ballou, J. E. 1981. Chemical Characterization and Toxicologic Evaluation of Airborne Mixtures. AD A102678, U.S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

Barnett, C. J., and J. E. Kontogiannis. 1975. "The Effect of Crude Oil Fractions on the Survival of a Tidepool Copepod, *Tigriopus californicus*." Environ. Pollut. 8:45-54.

Baur, J. E., R. P. Kerr, M. F. Bautista,C. J. Decker, and D. G. Capone. 1988. "Stimulation of Microbial Activities and Polycyclic Aromatic Hydrocarbon Degradation in Marine Sediments Inhabited by *Capitella capitata*." Mar. Environ. Res. 25(1):63-84.

Bausum, H.T., and G.W. Taylor. 1986. A Literature Survey and Data Base Assessment: Microbial Fate of Diesel Fuel and Fog Oils. Technical Report 8408, U.S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

Beck, L.S., D.I. Helpler, and K.L. Hansen. 1983. "The Acute Toxicology of Selected Petroleum Hydrocarbons." In Advances in Modern Environmental Toxicology, Volume 1: Applied Toxicology of Petroleum Hydrocarbons, ed. H.N. MacFarland. Princeton Scientific Publishers, Princeton, New Jersey.

Birkhead, R.R., C. Lloyd, and P. Corkhill. 1973. "Oiled Seabirds Successfully Cleaning Their Plumage." Br. Birds 66:353.

Blackburn, G.R., R.A. Deitch, C.A. Schreiner, M.A. Mehlman, and C.R. Mackerer. 1984. "Estimation of the Dermal Carcinogenic Activity of Petroleum Fractions Using a Modified Ames Assay." Cell Biol. Toxicol., 1:67-80.

Blumer, M., G. Souza, and J. Sass. 1970. "Hydrocarbon Pollution of Edible Shellfish by an Oil Spill." Marine Biology 5:195-202.

Blumer, M., H.L. Sanders, J.F. Grassle, and G.R. Hampson. 1971. "A Small Oil Spill." Environment 13(2):2-12.

Blumer, M., and J. Sass. 1972. "Oil Pollution: Persistence and Degradation of Spilled Fuel Oil." Science 176:1120-1122.

Bourne, W.R., and T.R. Devlin. 1969. "Birds and Oil." Birds 2:176-178.

Brahmachari, H.D. 1958. "Toxicity of White Oil." Current Sci. 27(11):440-441.

Buck, W.B., G.D. Osweiler, and G.A. Van Gelder. 1982. Clinical and Diagnostic Veterinary Toxicology, 2nd ed. Kendall/Hunt Publishing Company, Dubuque, Iowa.

Butler, C.A. 1974. Unpublished Conversation Record: Request for Information on Fog Oil, as reported by Liss-Suter, D., R. Mason, and P.N. Craig. (1978). Occupational Health and Safety Aspects of Diesel Fuel and White Smoke Generated for It. Vol. 1. Final Report. Report DAMD17-77-C-7020, AD A055903, for U.S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

Byrne, C. 1989. "Effects of the Water-Soluble Fractions of No. 2 Fuel Oil on the Cytokinesis of the Quahog Clam (Mercenaria mercenaria)." Bull. Environ. Contam. Toxicol. 42:81-86.

Byrne, C.J., and J.A. Calder. 1977. "Effect of the Water-Soluble Fractions of Crude, Refined and Waste Oils on the Embryonic and Larval States of the Quahog Clam Mercenaria sp." Marine Biology 40:225-231.

Cataldo, D.A., P. Van Voris, M.W. Ligotke, R.J. Fellow, B.D. McVeety, S.W. Li, H. Bolton, Jr., and J.K. Fredrickson. 1989. Transport, Transformations, Fate, and Terrestrial Ecological Effects of Fog Oil Obscurant Smokes. PNL-6799, Pacific Northwest Laboratory, Richland, Washington.

Chia, F.S. 1971. "Diesel Oil Spill at Anacortes." Mar. Pollut. Bull. 2(7):105-106.

Chipman, W.A., and P.S. Galtsoff. 1949. Effects of Oil Mixed with Carbonized Sand on Aquatic Animals. U.S. Fish Wildl. Serv., Spec. Sci. Rep. 1, 52 p.

Clark, R.C., Jr. and J.S. Finley. 1977. "Effects of Oil Spills in Arctic and Subarctic Environments." Eff. Pet. Arct. Subarct. Mar. Environ. Org. 2:411-476.

Clark, R. B., and J. R. Kennedy. 1968. Rehabilitation of Oiled Seabirds. Report to the Advisory Committee on Oil Pollution of the Sea (U.K.), Department of Zoology, The University of Newcastle upon Tyne, England.

Clean Air Act. 1990. 42 USC 7401, et seq., as amended.

Clean Water Act. 1977. 33 USC 1251, et seq., as amended.

Coleman, W. E., J. W. Munch, R. P. Streicher, H. P. Ringhand, and F. C. Kopfler. 1984. "The Identification and Measurement of Components in Gasoline, Kerosene, and No. 2 Fuel Oil that Partition into the Aqueous Phase after Mixing." Arch. Environ. Contam. Toxicol. 13:171-178.

Comprehensive Environmental Response, Compensation and Liability Act. 1980. 42 USC 9601, et seq., as amended by the Superfund Amendments and Reauthorization Act of 1980.

Cornelius, C. E., and J. J. Kaneko. 1963. Clinical Biochemistry of Domestic Animals. Academic Press, New York.

Crocker, A. D., J. Cronshaw, and W. N. Holmes. 1974. "The Effect of a Crude Oil on Intestinal Absorption in Ducklings (*Anas platyrhynchos*)." Environ. Pollut. 7:165-178.

Crocker, A. D., J. Cronshaw, and W. N. Holmes. 1975. "The Effect of Several Crude Oils and Some Petroleum Distillation Fractions on Intestinal Absorption in Ducklings (*Anas platyrhynchos*)." Envrion. Physiol. Biochem. 5:92-106.

Dauble, D. D., A. J. Scott, E. W. Lusty, B. L. Thomas, and R. W. Hanf, Jr. 1983. Ecotoxicity of Materials from Integrated Two-Stage Liquefaction and Exxon Donor Solvent Processes. PNL-4675, Pacific Northwest Laboratory, Richland, Washington.

Deichmann, W. B., K. V. Kitzmiller, S. Witherup, and R. Hoansmann. 1944. "Kerosene Intoxication." Ann. Intern. Med. 21-803-823.

Dobbs, F. C. 1981. "Community Ecology of a Shallow Sand flat, with Emphasis on Sediment Reworking by *Clymella torquata* (*Polychaeta: Maldanidae*).", M. S. Thesis, University of Connecticut, Storrs. Connecticut.

Dobbs, F. C. and R. B. Whitlach. 1982. "Aspects of Deposit Feeding by the Polychaete *Clymenella torquata*." Ophelia 21(2):159-166.

Driver, C. J., M. W. Ligotke, J. F. Bowers, and E. B. Moore, Jr. 1992a. An Environmental Assessment of the Production Prove-Out Test of the XM56 Dual-Purpose Smoke Generator: Arctic Test Conditions, U.S. Army Cold Regions Test Center, Fort Greely, Alaska. PNL-7984, Pacific Northwest Laboratory, Richland, Washington.

Driver, C. J., M. W. Ligotke, J. L. Downs, B.L. Tiller, T. Poston, E.B. Moore, Jr., and D. A. Cataldo, E. B. Moore, Jr. 1992b. Environmental and Health Effects Review for Obscurant Graphite Flakes PNL-8585, Pacific Northwest Laboratory, Richland, Washington.

Driver, C. J., M. W. Ligotke, J. L. Downs, J. P. Duncan, T. Poston, E. B. Moore Jr., and D. A. Cataldo, E. B. Moore, Jr. 1992c. Environmental and Health Effects Review for Obscurant Brass Flakes. PNL-XXXX, Pacific Northwest Laboratory, Richland, Washington.

Dunstan, W. M., L. P. Atkinson, and J. Natoli. 1975. "Stimulation and Inhibition of Phytoplankton Growth by Low Molecular Weight Hydrocarbons." Marine Biology 31:305-310.

Eberhard, W. L., R. E. Cupp, and N. L. Abshire. 1989. "Conservation Properties of Oil Fog Used as an Atmospheric Tracer." Atmos. Environ. 23(8):1855-1861.

Endangered Species Act. 1973. 16 USC 1531, et seq. as amended.

Falk, H. L., P. Kotin, and A. Mehler. 1964. "Polycyclic Hydrocarbons as Carcinogens for Man." Arch. Environ. Health 8(5):721-729.

Gearing, P. J., J. N. Gearing, R. J. Pruell, T. L. Wade, and J. G. Quinn. 1980. "Partitioning of No. 2 Fuel Oil in Controlled Estuarine Ecosystems. Sediments and Suspended Particulate Matter." Environ. Sci. Tech. 14(9):1129-1136.

Geraci, J. R. 1972. "Hypoatremia and the Need for Dietary Salt Supplementation in Captive pinnipeds." J. Am. Vet. Med. Assoc. 161:618-23.

Geraci, J. R., and T. G. Smith. 1975. "Functional Hematology of Ringed Seals (*Phoca hispida*) in the Canadian Arctic." J. Fish. Res. Board. Can. 32:2559-2564.

Geraci, J. R., and T. G. Smith. 1976. "Direct and Indirect Effects of Oil on Ringed Seals (*Phoca hispida*) of the Beaufort Sea." J. Fish. Res. Board Can. 33:1976-1984.

Geraci, J. R. and T. G. Smith. 1977. "Consequences of Oil Fouling on Marine Mammals." In Effects of Petroleum on Arctic and Subarctic Marine Envrionmentsl and organisms. Vol II. Biological Effects, ed. D. C. Malins. Academic Press, New York.

Gerarde, H. W. 1959. "Toxicology Studies on Hydrocarbons. V. Kerosene." Toxicol. Appl. Pharmacol. 1:462-474.

Gehring, P. J., R. J. Nolan, P. G. Watanabe, and A. M. schumann. 1991. "Solvents, Fumingants , and Related Compounds". In Handbook of Pesticide Toxicology. Vol. II: Classes of Pesticides, eds. W. J. Hayes, Jr. and E. R. Laws, Jr. Academic Press, New York.

Grau, C. R., M. T. Roudybush, J. Dobbs, and H. Wathen. 1977. "Altered Yolk Structure and Reduced Hatchability of Eggs from Birds Fed Single Doses of Petreoleum Oils." Science 195:(4280):779-781.

Grose, E. C., M. J. Selgrade, and K. Dean. 1985. Pulmonary and Systemic Health Effects of Acute and Subchronic Exposure to Smoke Obscurant SGF-2. EPA/600/D-85/201, U.S. NTIS PB86-102928, National Technical Information Service, Springfield, Virginia.

Grose, E. C., M. J. Selgrade, D. W. Davies, and A. G. Stead. 1986. Inhalation Toxicology of Fog Oil Smoke. Final Report. Health Effects Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Hartung, R. 1967. "Energy Metabolism in Oil-Covered Ducks." J. Wildl. Manage. 30:564-570.

Hartung, R., and G. S. Hunt. 1966. "Toxicity of Some Oils to Waterfowl." J. Wildl. Manage. 30:564-570.

Hazardous Materials Transportation Act. 1990. 49 USC 1801, et seq., as amended.

Hinds, W. C. 1982. Aerosol Technology. Wiley-Interscience, New York.

Holmes, W. N., and J. Cronshaw. 1977. "Biological Effects of Petroleum on Marine Birds." In Effects of Petroleum on Arctic and Subarctic Marine Environmental and Organisms. Vol II: Biological Effects, ed. D. C. Malins. Academic Press, New York.

Hunt, S. and H. E. Ewing. 1953. "Industrial Pollution and Michigan Waterfowl." In Eighteenth North American Wildlife Conference, ed. J. B Trefethen. Wildlife Management Institute, Wire Building, Washington, D. C.

Hunt, P. G., W. E. Rickard, F. J. Neneke, F. R. Koutz, and R. P. Murrman. 1973. "Terrestrial Oil Spills in Alaska: Environmental Effects and Recovery." In Proceedings of 1973 Joint Conference on Prevention and Control of Oil Spills. American Petroleum Institute, Washington D. C.

Ilandgovan, K., and M. Vivekanandan. 1989. "Long-Term Effects of Land Application of Aqueous Oil Effluent on Photosynthetic Efficiency of Certain Varieties of *Oryza sativa* L." Bull. Environ. Contam. Toxicol. 42:187-194.

IARC. 1984. "Polynuclear Aromatic Hydrocarbons, Part 2, Carbon Blacks, Mineral Oils (Lubricant Base Oils and Derived Products) and Some Nitroarenes." IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans 33:87-168.

Jacobson, S. M., and D. B. Boylan. 1973. "Effect of Seawater Soluble Fraction of Kerosene on Chemotaxis in a Marine Snail, *Nassarius obsoletus*." Nature 241:213-215.

Jones, T. C., and R. D. Hunt. 1983. Veterinary Pathology. 5th ed. Lea and Febiger, Philadelphia.

Katz, S., A. Snelson, R. Butler, R. Farlow, R. Welker, and S. Mainer. 1980. Physical and Chemical Characterization of Military Smokes: Part II - Fog Oils and Oil Fogs. Final Report. ADA093205, U.S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

Klaassen, C. D., M. O. Amdur, and J. Doull. 1986. Casarett and Doull's Toxicology, the Basic Science of Poisons, 3rd ed. Macmillan Publishing Company, New York.

Klein, D. R. 1976. The Reaction of Some Northern Mammals to Aircraft Disturbance. Alaska Cooperative Wildlife Research Unit, University of Alaska, Fairbanks, Alaska.

Koerting-Walker, C., and J. D. Buck. 1989. "The Effect of Bacteria and Bioturbation by *Clymenella torquata* on Oil Removal from Sediment." Water Air Soil Pollut. 43:413-424.

Kopischke, E. D. 1972. "The Effect of 2,4-D and Diesel Fuel on Egg Hatchability." J. Wildl. Manage. 36(3):1353-1356.

Larson, R. A., L. L. Hunt, and D. W. Blankenship. 1977. "Formation of Toxic Products from a No. 2 Fuel Oil by Photooxidation." Environ. Sci. Tech. 11(5):492-496.

Laughlin, R. B., Jr., L. G. L. Young, and J. M. Neff. 1978. "A Long-Term Study of the Effects of Water-Soluble Fractions of No. 2 Fuel Oil on the Survival, Development Rate, and Growth of the Mud Crab *Rhithropanopeus harrisii*." Marine Biology 47:87-95.

Lee, G. K., Jr., W. Y. Muse, Jr., and B. J. Brown. 1989. Mutagenic Responses of Some Petroleum-Based Obscurants in the Ames Test. CRDEC-TR-071, U.S. Army Armament Munitions Chemical Command, Aberdeen Proving Ground, Maryland.

Lee, W. Y., and J. A. C. Nicol. 1977. "The Effects of the Water Soluble Fractions of No. 2 Fuel Oil on the Survival and Behaviour of Coastal and Oceanic Zooplankton." Environ. Pollut. 12:279-292.

Lee, W. Y., S. A. Macko, and J. A. C. Nicol. 1981. "Changes in Nesting Behavior and Lipid Content of a Marine Amphipod (*Amphithoe valida*) to the Toxicity of a No. 2 Fuel Oil." Water Air Soil Pollut. 15:185-195.

Linden, O., J. R. Sharp, R. Laughlin, Jr., and J. M. Neff. 1979. "Interactive Effects of Salinity, Temperature and Chronic Exposure to Oil on the Survival and Developmental Rate of Embryos of the Estuarine Killifish *Fundulus hetervclitus*." Marine Biology 51:101-109

Liss-Suter, D., and J. E. Villaume. 1978. A Literature Review - Problem Definition Studies on Selected Toxic Chemicals. Volume 8 of 8. Environmental Aspects of Diesel Fuels and Fog Oils SGF No. 1 and SGF No. 2 and Smoke Screens Generated from Them. AD A056018, U.S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

Liss-Suter, D., J. E. Villaume, and P. N. Craig. 1978a. A Literature Review - Problem Definition Studies on Selected Toxic Chemicals. Volume 4 of 8. Occupational Health and Safety Aspects of the Fog Oils SGF No. 1 and SGF No. 2 and Smoke Screens Generated from Them. AD A056018, U.S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

Liss-Suter, D., R. Mason, and P. N. Craig. 1978b. A Literature Review - Problem Definition Studies on Selected Toxic Chemicals. Volume 1 of 8. Occupational Health and Safety Aspects of Diesel Fuel and White Smoke Generated from It. Report DAMD17-77-C-7020, AD A056018, U.S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

Lushbaugh, C. C., J. W. Green, Jr., and C. E. Redemann. 1950. "Effects of Prolonged Inhalation of Oil Fogs on Experimental Animals." Arch. Ind. Hyg. Occup. Med. 1:237-247.

Mackie, P. R., A. S. McGill, and R. Hardy. 1972. "Diesel Oil Contamination of Brown Trout." Environ. Pollut. 3(1):9-16.

Manthei, J. H., M. Donnelly, F. K. Lee, Jr., and J. T. Weimer. 1980. Preliminary Toxicity Screening Studies of 11 Smoke Candidate Compounds. ARCSL-TR-79056, U.S. Army Chemical Systems Laboratory, Aberdeen Proving Ground, Maryland.

Mayhew,D. A., S. H. Smith, G. L. Doyle, J. C. Kreuger, and K. A. Mellon. 1986. Dermal, Eye, and Oral Toxicologic Evaluations of Brass Powder, Fog Oil, diesel fuel, and Their Mixtures. AD-A172-198, U.S. Army Medical Research and Development Command, Fort Detrick, Frederick, Maryland.

McEwan, E. H., N. Aitchison, and P. E. Whitehead. 1974. "Energy Metabolism of Oiled Muskrats." Can J. Zool. 52:1057-62.

McNamara, B. P. 1963. "Effects from Exposure to Aerosols of Fog Oil." In 1978 Occupational Health and Safety Aspects of Diesel Fuel and White Smoke Generated From It. Vol. 1., eds. D.

Liss-Suter, R. Mason, and P.N. Craig. AD A056018, U.S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

MERCK. 1983. The MERCK Index, 10th ed. Merck & Co., Rahway, New Jersey.

Miller, F. J., D. E. Gardner, H. A. Graham, R. E. Lee, Jr., W. E. Wilson, and J. D. Bachmann. 1979. "Size Considerations for Establishing a Standard for Inhalable Particles." J. Air Pollut. Control Assoc. 29:610-615.

Muhly, R. L. 1983. Programmatic Life Cycle Environmental Assessment for Smoke/Obscurants. Volume 1: Fog Oil, Diesel Fuels, and Polyethylene Glycol (Peg 200). ARCSL-EA-83001, U.S. Army Chemical Research, Development and Engineering Center, Aberdeen Proving Ground, Maryland.

Occupational Safety and Health Act. 1970. 29 USC 651, et seq., as amended.

Osmitz, T. G., W. E. Dalbey, C. Kommineni, and E. J. Singer. 1987. "30-Day Inhalation Exposures of Sprague-Dawley Rats to Aerosolized Lubricant Base Oils." Toxicologist 7:203.

Palmer, W. G. 1990. Exposure Standard for Fog Oil. Technical Report 9010, U.S. Army Biomedical Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

Percy, J. A., and T. C. Mullin. 1977. "Effects of Crude Oil on the Locomotory Activity of Arctic Marine Invertebrates." Mar. Pollut. Bull. 8:35-40.

Pereira, M. A., ed. 1983. "International Symposium on Tumor Promotion." Environ. Health Perspect. 50:3-370.

Phalen, R. F. 1984. Inhalation Studies: Foundations and Techniques. CRC Press, Boca Raton, Florida.

Poston, T. M., K. M. McFadden, R. M. Bean, M. L. Clark, B. L. Thomas, B. W. Killand, L. A. Prohammer, and D. R. Kalkwarf. 1986. Acute Toxicity of Smoke Screen Materials to Aquatic Organisms, White Phosphorus-Felt, Red Phosphorus-Butyl Rubber and SGF No. 2 Fog Oil. U.S. Army Medical Research and Development Command, Fort Detrick, Frederick, Maryland.

Poston, T. M., R. M. Bean, D. R. Kalkwarf, B. L. Thomas, M. L. Clark, and B. W. Killand. 1988. "Photooxidation Products of Smoke Generator Fuel (SGF) No. 2 Fog Oil and Toxicity to *Hyallela azteca*." Environ. Tox. Chem. 7:753-762.

Raymond, R. L., J. O. Hudson, and V. W. Jamison. 1976. "Oil Degradation in Soil." Appl. Environ. Microbiol. 31:522535.

Reimer, A. A. 1975. "Effects of Crude Oils on Corals." Mar. Pollut. Bull. 6(3):39-43.

Regnier, Z. R., and B. F. Scott. 1975. "Evaporation Rates of Oil Components." Environ. Sci. Technol. 9(5):469-472.

Resource Conservation and Recovery Act. 1976. 42 USC 6901, et seq., as amended.

Rhoads, D. C. and L. F. Boyer. 1982. "The Effects of Marine Benthos on Physical Properties of Sediments". In Animal-Sediment Relations, eds. P.L. McCall and M. J. S. Tevesz, Plenum Publ. New York. pp. 3-52.

Rossi, S. S., J. W. Anderson, and G. S. Ward. 1976. "Toxicity of Water-Soluble Fractions of Four Test Oils for the Polychaetous Annelids, *Neanthes arebaceidebtata* and *Capitella capitata*." Environ. Pollut. 10:9-18.

Rowe, L. D., J. W. Dollahite, and B. J. Camp. 1973. "Toxicity of Two Crude Oils and Kerosene to Cattle." JAVMA 162-61-66.

Safe Drinking Water Act. 1986. 42 USC 300f, et seq., as amended.

Scheier, A., and D. Gominger. 1976. "A Preliminary Study of the Toxic Effects of Irradiated vs. Non-Irradiated Water Soluble Fractions of #2 Fuel Oil." Bull. Environ. Contam. Toxicol. 16(5):595-603.

Selgrade, M. K., G. E. Hatch, E. C. Grose, J. W. Illing, A. G. Stead, F. J. Miller, and J. A. Graham. 1987. "Pulmonary Effects Due to Short-Term Exposure to Oil Fog." J. Toxicol. Environ. Health 21:173-185.

Selgrade, M. K., G. E. Hatch, E. C. Grose, A. G. Stead, F. J. Miller, and J. A. Graham. 1990. "Pulmonary Effects Due to Subchronic Exposure to Oil Fog." Toxicol. Indust. Health 6(1):123-143.

Shinn, J. H., S. A. Martins, P. L. Cederwall, and L. B. Gratt. 1985. Smokes and Obscurants: A Health and Environmental Effects Data Base Assessment. A First-Order, Environmental Screening and Ranking of Army Smokes and Obscurants. Phase I Report. U.S. Army Medical Research and Development Command, Fort Detrick, Frederick, Maryland.

Singh, B., and H. P. Sharma. 1970. "Control of Bandha [*Dendrophthoe falcata* (L.F.) Ettingsh], II. Effect of Diesel Oil Spray on the Respiration of the Leaf of the Parasite." Proc. Ind. Acad. Sci. 71:109-117.

Smith, J. E. 1968. Torrey Canyon Pollution and Marine Life: A Report by the Plymouth Laboratory, Vol. 14. Cambridge University Press, Cambridge.

Smith, L. H., M. L. Daugherty, and J. G. Pruett. 1987. The Toxicity of Diesel Fuels, and JP-8 Aviation Fuels in Mammals and Environmental Species. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Smith, T. G., and J. R. Geraci. 1975. The Effect of Contact and Ingestion of Crude Oil on Ringed Seals of the Beaufort Sea. Beaufort Sea Tech. Report 5, Environment Canada, Victoria, British Columbia, Canada.

Starek, A., L. Fiema, D. Cembala, and W. Lepiarz. 1975. "Comparing Toxicity of Certain Oil Products Used as Dielectrics in Electroerosive Working. I. Acute and Subacute Toxicity." Med. Pr. 26(3):219-230.

Stula, E. F., and B. K. Kwon. 1978. "Pulmonary Pathology from Inhalation of a Complex Mineral Oil Mist in Dogs, Rats, Mice and Gerbils." Amer. Ind. Hyg. Assoc. J. 39:393-399.

Sullivan, J. D., and R. G. Reitz. 1980. Fuel-Air Explosions in a Fog Oil Smoke Environment. Memorandum Report ARBRL-MR-02985, U.S. Army Armament Research and Development Command, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland.

Szaro, R. C., and P. H. Albers. 1976. "Effects of External Applications of Oil on Common Eider Eggs." In Proceedings of Symposium on Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms, ed. D. Wolfe. Pergamon Press, New York.

Tagatz, M. E. 1961. "Reduced Oxygen Tolerance and Toxicity of Petroleum Products to Juvenile American Shad." Chesapeake Sci. 2(1-2):65-71.

Takahashi, F. T. and J. S. Kittredge. 1973. "Sublethal Effects of the Water Soluble Component of Oil: Chemical Communication in the Marine Environment." In The Microbial Degradation of Oil Pollutants, eds. D. G. Ahearn and S. P. Meyers. Publ. No. LSU-SG-73-01. Center Wetland Resources, Louisiana State University, Baton Rouge, Lousisanna.

Tarzwell, C. M. 1931. "Oil Spill Toxicity." Chem. Eng. News 49(22):26

Tarzwell, C. M. 1971. "Measurement of Pollution Effects on Living Organisms. I: Bioassays to Determine Allowable Waste Concentrations in the Aquatic Environment." Proc. R. Soc. Lond. B. Biol Sci. 177:279-285.

U.S. Army. 1975. Generator, Smoke, Mechanical, Pulse Jet, M3A3. U.S. Army Technical Manual, TM 3-1040-202-12, Department of the Army, Washington, D.C.

U.S. Army. 1986. Workshop to Select Test Systems for Ecological Assessment and Monitoring. January 19-22, 1986, U.S. Army Construction Engineering Research Laboratory (CERL), University of Illinois at Urbana-Champaign, Illinois.

Van Voris, P., D. A. Cataldo, M. W. Ligotke, T. R. Garland, K. M. McFadden, J. K. Fredrickson, S. W. Li, R. M. Bean, B. L. Thomas, and D. W. Carlile. 1987. Evaluate and Characterize Mechanisms Controlling Transport, Fate, and Effects of Army Smokes in the Aerosol Wind Tunnel: Transport, Transformations, Fate, and Terrestrial Ecological Effects of Red Phosphorus-Butyl Rubber and White Phosphorus Obscurant Smokes. PNL-6071, Pacific Northwest Laboratory, Richland, Washington.

Vanderhorst, J. R., C. I. Gibson, and L. J. Moore. 1976. "The Role of Dispersion in Fuel Oil Bioassay." Bull. Environ. Contam. Toxicol. 15(1):93-100.

Warner, M. L., R. H. Sauer, and D. W. Carlile. 1984. "Barley Growth in Coal Liquid and Diesel Liquid Fuels from Coal and Oil: A Comparison of Potential Toxic Effects on Barley." Water Air Soil Pollut. 22:47-55.

Yanders, A. F., E. W. Novak, and W. R. Lower. 1985. "Mutagenic Testing of 'Obscurant Smokes'." Environ. Mutagen. 7(3):60.

Yingst, J. Y. and D. C. Rhoads. 1980. Marine Benthic Dynamics. South Carolina press, Columbia, South Carolina. p. 407.

Young, J. Y., D. A. Smart, J. T. Allen, D. L. Parmer, A. B. Rosencrance, E. E. Brueggemann, and F. H. Broski. 1989. Field Exposure of Chemical School Students and Cadre to Fog Oil and Hexachlorethane (HC) Smokes. Technical Report no. 8908, U.S. Army Biomedical Research and Development Laboratory, Fort Detrick, Frederick, Maryland.

Zurcher, F., and M. Thuer. 1978. "Rapid Weathering Processing of Fuel Oil in Natural Waters: Analyses and Interpretations." Environ. Sci. Tech. 12(7):838-845.

Blank

APPENDIX

AERIAL DISPERSION AND DEPOSITION OF FOG OIL IN THE ENVIRONMENT

The dispersion of fog oil aerosols from a point of release and their subsequent deposition to downwind areas are influenced by the aerodynamic characteristics of the recondensed liquid fog oil particles and by the local meteorological conditions, site geography, and surface terrain. Because of the adhesive nature of fog oil, deposited residues will be less likely than other smoke materials (such as graphite flakes) to be resuspended during wind storms, and so subsequent environmental fate and impact are more likely to occur at the location of initial deposition. However, when the fog oil is mixed in air with battlefield dust or graphite flakes, its dispersion from the site, deposition rates, environmental impact, and susceptibility to resuspension may be altered. Data describing these processes are lacking. In addition, because of the fluctuating state of meteorological conditions and the irregularities of site terrain, the pattern and magnitude of aerial dispersion and deposition at a specific site will vary from test to test and will be different from those for other sites. The dissemination system will also influence plume dispersion and deposition via such operational parameters as generation rate, duration of operations, temperature and angle of exhaust flow, and the initial effective plume height of the fog oil.

Estimates of the dispersion, air concentration, and deposition of fog oil are necessary to evaluate the potential impact of specific tests and training activities on the environment. General predictions of the pattern of fog oil plume dispersion and deposition for an ideal site were made for pure fog oil aerosols using a Gaussian plume dispersion model (e.g., Wark and Warner 1976) that was modified to include source depletion and the gravitational settling and removal of suspended fog oil particles. The Gaussian model was selected because it is the most basic and most commonly used dispersion model and for the following reasons as summarized by Hanna et al. (1982).

1) It produces results that agree with experimental data as well as those of any other model.
2) It is fairly easy to perform mathematical operations on the equation.
3) It is appealing conceptually.
4) It is consistent with the random nature of turbulence.
5) It is a solution to the Fickian diffusion equation for constants K (eddy diffusion) and u (wind speed).
6) Other so-called theoretical formulas in fact contain large amounts of empiricism in their final stages.

There are two primary differences between the predictions based on the Gaussian model and the pattern of deposition likely to be seen in the field. First, although model results indicate gradual changes in air concentration and surface deposition with increasing downwind distance from the source, survey of an actual field site may reveal areas of fog oil deposition maxima and minima. Second, the model assumes a wind vector that is constant in direction and time, whereas the deposition of fog oil in the field will reflect site terrain and the fluctuating nature of the mean wind vector. Deposition may also be greater than normal immediately downwind of the generator and may be partially enhanced by wind eddies formed in the lee of the smoke generator. These differences between model predictions and field conditions will affect both local and long-range transport from the point of release. For the transport of fog oil from specific sites under well-defined conditions, and after an analysis of the benefit of potentially improved plume dispersion estimates, more sophisticated models or models prepared for specific sites can be applied on a case-by-case basis. One such model is the Industrial Source Complex Dispersion Model (Wackter and Foster 1986). Another is the Real-Time Volume Source Dispersion Model (Bjorklund 1990), which is currently widely accepted and is used by staff at the Meteorology Division, U.S. Army Dugway Proving Grounds, Utah.

Plume Dispersion and Deposition Model

The modified Gaussian plume dispersion model provides an estimate of the concentration of fog oil in air at locations downwind of the point of release as defined by coordinates x, y, and z, where x is the downwind coordinate, y is the crosswind coordinate, and z is the vertical coordinate:

$$C(x,y,z,H) = (Q_x/Q_p)(2\pi u s_y s_z)^{-1} \exp\{-0.5[(y/s_y)^2 + (\{z-[H-V_s(x/u)]\}/s_z)^2]\} \qquad (A.1)$$

In the equation, Q_p is the mass rate of fog oil generation, in g/s; u is the magnitude of the mean wind, in m/s; H is the height of the plume at the point of release; V_s is the settling velocity of fog oil droplets in the plume, in cm/s; and s_y and s_z are the standard deviations of plume dispersion in the y and z coordinates, respectively, expressed in meters. The leading term in Equation (A.1), Q_x/Q_p, is a source-depletion term that accounts for the reduction in the total windborne mass of a smoke plume that results as deposition occurs between the site of dissemination and a given downwind distance. The quantity Q_x/Q_p is determined numerically (Van der Hoven 1968; Hanna et al. 1982). The model assigns values to the crosswind and vertical standard deviations of plume dispersion as functions of the atmospheric stability category (ASC), which in turn is influenced by wind speed and insolation level. Plume reflection from the top of a mixing layer is not considered in the model.

To estimate the rate of fog oil deposition to ground surfaces per unit of surface area, w in g/(m^2-s), Equation (A.1) was converted using the relationship:

$$w(x,y,0,H) = V_d C(x,y,0,H) \qquad (A.2)$$

In Equation (A.2), V_d is the deposition velocity of fog oil droplets, a parameter that is generally greater than V_s for small particles. Using Equation (A.2), the deposition of fog oil to ground surfaces, ML in g/m^2, was estimated by multiplying w by the duration of fog oil dissemination, Δt, in seconds:

$$ML(x,y,0,H) = w(x,y,0,H)\Delta t = C(x,y,0,H)V_d\Delta t \qquad (A.3)$$

The model parameters include Q_p, H, u, ASC, V_s, V_d, and Δt. Estimates for six test cases were determined as average air concentration downwind of the source and at an elevation of 1 m, Cm, and surface mass loading, ML. Each test case is described in Table A.1. Cases 2 and 3 represent typical conditions. Case 1 represents extremely unstable atmospheric conditions during which tactical release of obscurant smoke may be least effective because of rapid plume dispersion (but during which smoke testing may pose the least environmental risk because of low resulting concentrations and deposition levels). Although Case 4 represents moderately stable atmospheric conditions (ASC F) that are not common at most sites, it was included because it represents a worst-case condition. Cases 5 and 6 were selected to demonstrate the predicted impact of wind speed and plume height, respectively. Both cases were assigned ASC C and differ from Case 2 by only a single parameter.

To provide general air concentration and surface deposition levels for the six test cases, values for Pasquill-type ASC were determined based on information in Table A.2 (Gifford 1976; Hanna et al. 1982). The plume dispersion parameters s_y and s_z were calculated based on the open-country formulas recommended by Briggs (1973) and shown in Table A.3.

TABLE A.1. Test Cases for Estimating Fog Oil Plume Dispersion in the Atmosphere and Deposition to Ground Surfaces

Case	Parameter	Q_p (g/s)	H (m)	u (m/s)	ASC	V_d (cm/s)	Δt (min)
1	ASC	77	5	2	A	0.06	30
2	ASC	77	5	2	C	0.06	30
3	ASC	77	5	5	D	0.6	30
4	ASC	77	5	2	F	0.06	30
5	u	77	5	5	C	0.6	30
6	H	77	10	2	C	0.06	30

TABLE A.2. Meteorological Conditions Defining Pasquill Turbulence Types [after Gifford (1976) and Hanna et al. (1982)]

Surface Wind Speed, m/s	Daytime Insolation			Nighttime Conditions	
	Strong	Moderate	Slight	Thin Overcast or > 4/8 Low Cloud	≤ 3/8 Cloud
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

Atmospheric conditions: A=extremely unstable; B=moderately unstable; C=slightly unstable; D-neutral; E=slightly stable; and F=moderately stable.

TABLE A.3. Formulas for Determining s_y and s_z for Atmospheric Plume Dispersion Estimates for 0.1 to 10 km (Briggs 1973)

Pasquil ASC	s_y (m)	s_z (m)
Open-Country Conditions		
A	$0.22x(1+0.0001x)^{-1/2}$	$0.20x$
B	$0.16x(1+0.0001x)^{-1/2}$	$0.12x$
C	$0.11x(1+0.0001x)^{-1/2}$	$0.08x(1+0.0002x)^{-1/2}$
D	$0.08x(1+0.0001x)^{-1/2}$	$0.06x(1+0.0015x)^{-1/2}$
E	$0.06x(1+0.0001x)^{-1/2}$	$0.03x(1+0.0003x)^{-1}$
F	$0.04x(1+0.0001x)^{-1/2}$	$0.016x(1+0.0003x)^{-1}$
Urban Conditions		
A-B	$0.32x(1+0.0004x)^{-1/2}$	$0.24x(1+0.001x)^{1/2}$
C	$0.22x(1+0.0004x)^{-1/2}$	$0.20x$
D	$0.16x(1+0.0004x)^{-1/2}$	$0.14x(1+0.0003x)^{-1/2}$
E-F	$0.11x(1+0.0004x)^{-1/2}$	$0.08x(1+0.00015x)^{-1/2}$

The fog oil plume dispersion and deposition estimates were made for the commonly used release rate (Q_p) of 77 g/s (80 gal/h), which is the nominal dissemination rate for fog oil of the XM56 obscurant generator; use of smoke pots will involve rates of about 10 g/s, and the M52 rates of about 870 g/s (see Section 2.4.1). The plume height (H) was estimated to be 5 m, a value that approximates the minimal plume rise during optimum conditions for generating a near-ground obscurant cloud. For Case 6, the initial plume height was selected to be 10 m. For specific tests, plume-rise should be considered and a modified H determined if fog oil aerosols are to be generated under other conditions. Wind speed (u) was assumed to range between 2 and 5 m/s (2 and 11 mph). Test cases were selected that spanned the range of expected stability conditions. In general, ASC A and B provide poor obscuration but good atmospheric mixing, and ASC D may provide good obscuration. ASC E and F are less common. The settling velocity (V_s) for fog oil droplets was estimated to be 0.02 cm/s (although greater than the V_s of the AMMD, this velocity is still too small to influence the plume dispersion estimates). The deposition velocity V_d was selected to be 0.06 and 0.6 cm/s, for wind speeds of 2 and 5 m/s, respectively (Cataldo et al. 1989, 1990). Finally, Δt was selected to be 30 min, based on operational characteristics of the XM56. This duration is expected to be greatly exceeded at some installations over periods of hours, days, or years because of testing or training activities. For multiple generators located close together, Cm will be an approximate scalar value of the Cm predicted for a single generator times the number of actual generators used for a given test or training activity. Multiple generators that are well spaced will result in a value for Cm that is dependent on the spacing of the generators as well as downwind distance.

The influences of values of Q_p and u on air concentration and the influences of Q_p, u, V_d, and Δt on surface deposition in situations that differ from the six test cases may be estimated by scaling specific values to those determined for the test case having the same ASC. This simple estimation is possible because the exponential function of Equations A.1 and A.2 is close to unity for the expected ranges of the parameters. For example, if fog oil aerosols are dispersed at a rate Q_p' that differs from the nominal rate, air concentration and surface deposition estimates may be determined by directly scaling the results by the ratio of Q_p' to Q_p (e.g., $Cm' = Cm[Q_p'/Q_p]$ and

ML' = ML[Q_p'/Q_p]). Other scalable relationships include Cm' = Cm(u/u'); ML' = ML(u/u'); ML' = ML(V_d'/V_d); and ML' = ML(Δt'/Δt). These relationships neglect the influence of plume depletion, but should be fairly accurate given the low plume depletion rates of fog oil (see below). No Cm and ML estimates for ASC B and E were determined, but estimates may be obtained mathematically by application of the model or graphically by simply interpolating between ASC A and C for B, or between D and F for E. The influence of alternate values of H cannot be scaled but are limited for moderate changes in H (about 2 to 20 m).

Plume Dispersion and Deposition Model Results

Results of estimated fog oil dispersion and deposition are shown for selected test cases in Figures A.1 through A.4 and for all test cases in Tables A.4 through A.7. For clarity, only cases 1 through 4 only are shown in Figures A.1 and A.2. For comparison (especially with Case 2), Cases 5 and 6 are shown in Figures A.3 and A.4. The parameters used for each test case are listed in the upper left-hand corner of each table and in Table A.1. Estimates were made for downwind distances between 0.1 and 40 km (0.06 to 25 mi), and for crosswind locations 1 and 10 km downwind of the source. In all cases, the estimates were made assuming a constant wind vector; under conditions of fluctuating wind direction, the 30-min average air concentrations and deposition levels would be less than those determined by the model. The fog oil aerosol concentration, Cm and Cm*, was estimated for each location at an elevation of 1 m using Equation A.1. The concentration estimate Cm is made assuming no surface reflection, and Cm* is the estimate made assuming 100% surface reflection. Because the actual reflection coefficient is not known for fog oil aerosols, Cm* was considered to be the most conservative result (the difference between Cm and Cm* is a factor of 2 except close to the generator). Consequently, results for each test case were plotted using Cm*.

Windborne fog oil concentrations at the plume centerline for Cases 1, 2, 3, and 4 (shown in Figure A.1) generally decreased from 7 - 140 mg/m^3 at downwind distances of 0.1 - 0.2 km, to less than 0.003 - 0.3 mg/m^3 at a distance of 40 km. The greatest air concentrations are likely to occur within 0.1 km of the source for Cases 1 through 3. Because of the very limited lateral and vertical plume dispersion caused by the moderately stable ASC F conditions, the greatest concentration near the ground for Case 4 would occur between 0.1 and 0.4 km downwind of the source. In addition, the decrease in plume concentration that occurs with increasing downwind distance is markedly less for Case 4 than for the other cases, for which less stable atmospheric conditions were assigned. At comparable downwind distances, air concentration estimates for the test cases varied by a factor of 4 to 250. Crosswind profiles (Tables A.4 and A.6) indicated progressively wider plumes for unstable atmospheric conditions (with ASC A being the extreme case). However, as is the case for the centerline plume concentration estimates, crosswind estimates are likely to be conservative (too great) unless air flow is very uniform in direction. Air concentrations exceeding 10 mg/m^3 (the STEL for fog oil [see Section 2.5.1]) were predicted to potentially occur within downwind distances of 0.4 km from the source for all cases except Case 4, for which such concentrations may be exceeded within about 2 km of the source. Assuming continuous generation of fog oil for a 24-h period, the 150-µg/m^3 NAAQS (see Section 3.1) would be exceeded at distances within about 2 to 40 km of the source, depending on atmospheric conditions (Figure A.1). For a single 30-min release of fog oil in a 24-h period, the NAAQS would be exceeded within about 0.2 to 3 km of the source, again depending on atmospheric conditions.

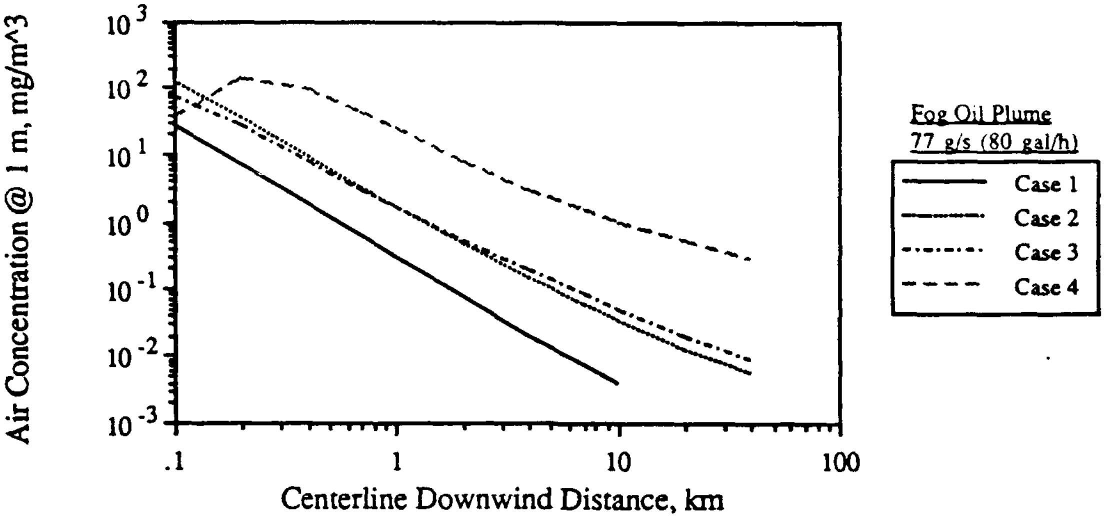

FIGURE A.1. Estimated Atmospheric Dispersion of Fog Oil Plumes, Cases 1 Through 4. Concentrations were determined using a modified Gaussian plume dispersion model and at an elevation of 1 m. For clarity, only Cases 1 through 4 are shown.

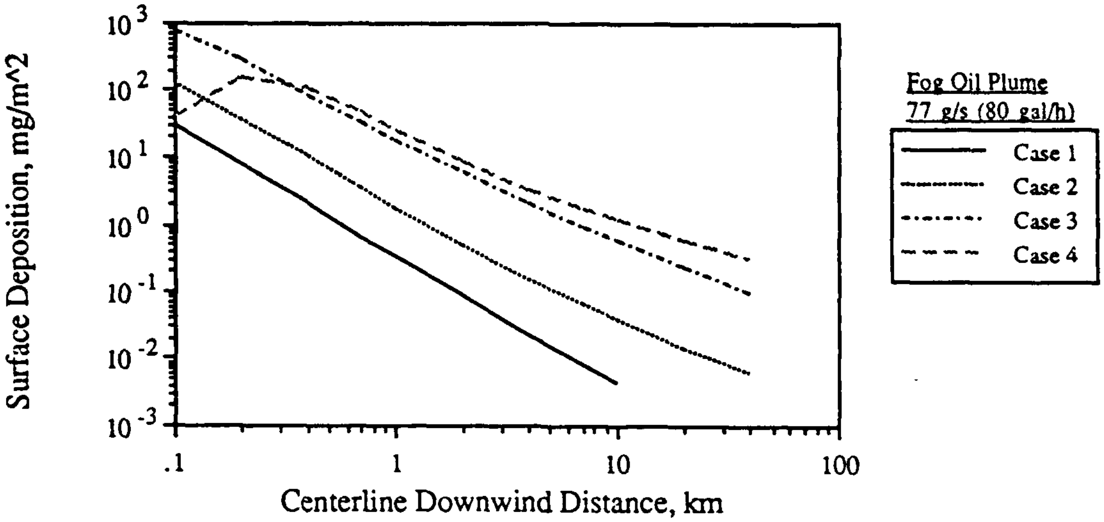

FIGURE A.2. Estimated Fog Oil Surface Deposition Levels, Cases 1 Through 4. Mass loading was determined using a modified Gaussian plume dispersion model. For clarity, only Cases 1 through 4 are shown.

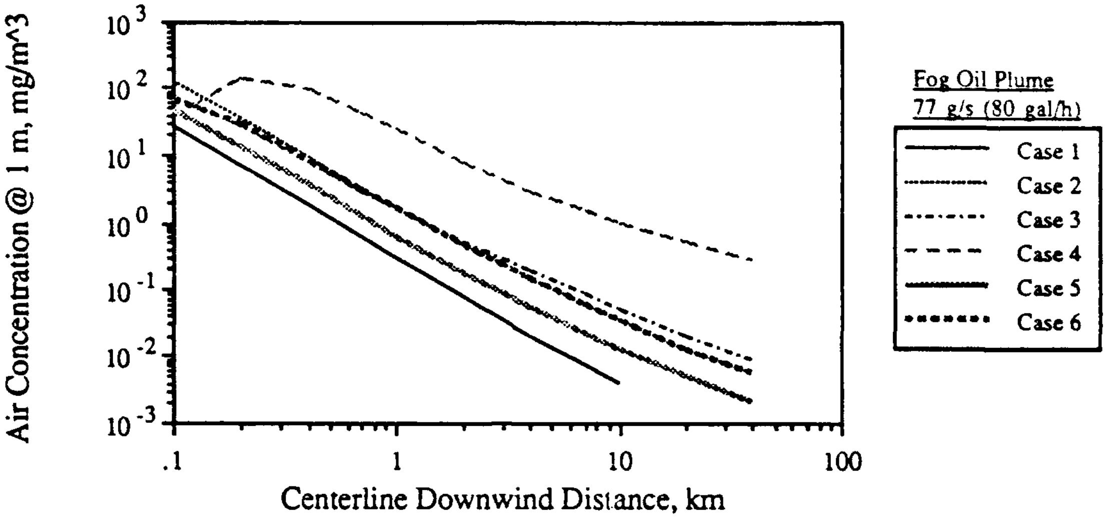

FIGURE A.3. Estimated Atmospheric Dispersion of Fog Oil Plumes, Cases 1 Through 6. Concentrations were determined using a modified Gaussian plume dispersion model and at an elevation of 1 m. Cases 5 and 6 were similar to Case 2 (2 m/s at 5 m) with the exception of wind speed (Case 5, 5 m/s) and initial plume height (Case 6, 10 m).

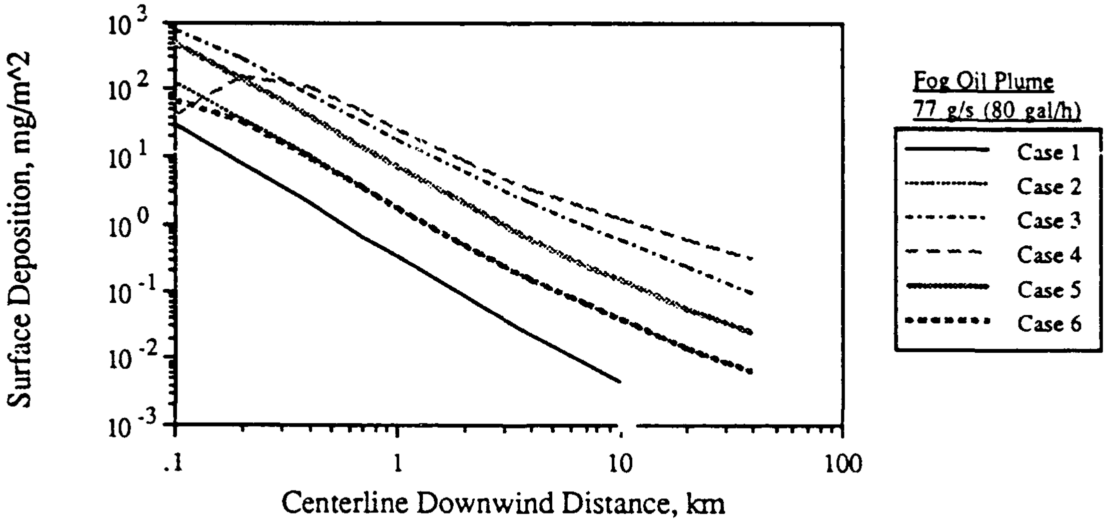

FIGURE A.4. Estimated Fog Oil Surface Deposition Levels, Cases 1 Through 6. Mass loading was determined using a modified Gaussian plume dispersion model. Cases 5 and 6 were similar to Case 2 (2 m/s at 5 m) with the exception of wind speed (Case 5, 5 m/s) and initial plume height (Case 6, 10 m).

TABLE A.4. Fog Oil Dispersion and Deposition Estimates Using a Modified Gaussian Plume Model for Cases 1, 2, and 3

Case:	No. 1	x (km)	y (km)	Sig. y	Sig. z	Qx/Qp	Cm (mg/m^3)	Cm* (mg/m^3)	ML (mg/m^2)
Qp (g/s) =	77	0.1	0	22	20	1.00	1.4 e+01	2.7 e+01	2.9 e+01
u (m/s) =	2	0.2	0	44	40	1.00	3.5 e+00	7.0 e+00	7.5 e+00
ASC =	A	0.4	0	86	80	1.00	8.8 e-01	1.8 e+00	1.9 e+00
H (m) =	5	0.7	0	149	140	1.00	2.9 e-01	5.9 e-01	6.3 e-01
Δt (min) =	30	1	0	210	200	1.00	1.5 e-01	2.9 e-01	3.1 e-01
z (m) =	1	2	0	402	400	0.99	3.8 e-02	7.6 e-02	8.2 e-02
Vs (cm/s) =	0.02	4	0	744	800	0.99	1.0 e-02	2.0 e-02	2.2 e-02
Vd (cm/s) =	0.06	7	0	1181	1400	0.99	3.7 e-03	7.4 e-03	8.0 e-03
Srce-Depl:	yes	10	0	1556	2000	0.99	2.0 e-03	3.9 e-03	4.2 e-03
Iterations =	100	20	0	2540	N D				
Type =	rural	40	0	3935	N D				
Cm (0% reflection)		1	0.1	210	200	1.00	1.3 e-01	2.6 e-01	2.8 e-01
Cm* (100% reflection)		1	0.2	210	200	1.00	9.2 e-02	1.8 e-01	2.0 e-01
ML (surface loading)		1	0.4	210	200	1.00	2.4 e-02	4.7 e-02	5.1 e-02

Case:	No. 2	x (km)	y (km)	Sig. y	Sig. z	Qx/Qp	Cm (mg/m^3)	Cm* (mg/m^3)	ML (mg/m^2)
Qp (g/s) =	77	0.1	0	11	8	1.00	6.2 e+01	1.2 e+02	1.2 e+02
u (m/s) =	2	0.2	0	22	16	1.00	1.7 e+01	3.4 e+01	3.7 e+01
ASC =	C	0.4	0	43	31	0.99	4.5 e+00	9.0 e+00	9.8 e+00
H (m) =	5	0.7	0	74	52	0.99	1.6 e+00	3.1 e+00	3.3 e+00
Δt (min) =	30	1	0	105	73	0.99	7.9 e-01	1.6 e+00	1.7 e+00
z (m) =	1	2	0	201	135	0.99	2.2 e-01	4.5 e-01	4.8 e-01
Vs (cm/s) =	0.02	4	0	372	239	0.99	6.8 e-02	1.4 e-01	1.5 e-01
Vd (cm/s) =	0.06	7	0	591	361	0.98	2.8 e-02	5.6 e-02	6.1 e-02
Srce-Depl:	yes	10	0	778	462	0.98	1.7 e-02	3.4 e-02	3.6 e-02
Iterations =	100	20	0	1270	716	0.98	6.6 e-03	1.3 e-02	1.4 e-02
Type =	rural	40	0	1968	1067	0.98	2.9 e-03	5.7 e-03	6.2 e-03
Cm (0% reflection)		1	0.1	105	73	0.99	5.0 e-01	1.0 e+00	1.1 e+00
Cm* (100% reflection)		1	0.2	105	73	0.99	1.3 e-01	2.6 e-01	2.8 e-01
ML (surface loading)		1	0.4	105	73	0.99	5.5 e-04	1.1 e-03	1.2 e-03

Case:	No. 3	x (km)	y (km)	Sig. y	Sig. z	Qx/Qp	Cm (mg/m^3)	Cm* (mg/m^3)	ML (mg/m^2)
Qp (g/s) =	77	0.1	0	8	6	0.99	4.2 e+01	7.3 e+01	7.9 e+02
u (m/s) =	5	0.2	0	16	11	0.98	1.3 e+01	2.6 e+01	2.8 e+02
ASC =	D	0.4	0	31	19	0.97	3.9 e+00	7.7 e+00	8.3 e+01
H (m) =	5	0.7	0	54	29	0.96	1.5 e+00	2.9 e+00	3.2 e+01
Δt (min) =	30	1	0	76	38	0.95	8.0 e-01	1.6 e+00	1.7 e+01
z (m) =	1	2	0	146	60	0.93	2.6 e-01	5.2 e-01	5.6 e+00
Vs (cm/s) =	0.02	4	0	270	91	0.91	9.1 e-02	1.8 e-01	2.0 e+00
Vd (cm/s) =	0.6	7	0	430	124	0.89	4.1 e-02	8.2 e-02	8.8 e-01
Srce-Depl:	yes	10	0	566	150	0.87	2.5 e-02	5.0 e-02	5.4 e-01
Iterations =	100	20	0	924	216	0.83	1.0 e-02	2.0 e-02	2.2 e-01
Type =	rural	40	0	1431	307	0.78	4.3 e-03	8.7 e-03	9.4 e-02
Cm (0% reflection)		1	0.1	76	38	0.95	3.4 e-01	6.8 e-01	7.3 e+00
Cm* (100% reflection)		1	0.2	76	38	0.95	2.6 e-02	5.1 e-02	5.6 e-01
ML (surface loading)		1	0.4	76	38	0.95	8.6 e-07	1.7 e-06	1.8 e-05

* Continuous generation, source-depleting, tilting plume, 0.1 km ≤ x ≤ 40 km.

TABLE A.5. Fog Oil Dispersion and Deposition Estimates Using a Modified Gaussian Plume Model for Cases 4, 5, and 6

Case:	No. 4	x (km)	y (km)	Sig. y	Sig. z	Qx/Qp	Cm (mg/m^3)	Cm* (mg/m^3)	ML (mg/m^2)
Qp (g/s) =	77	0.1	0	4	2	1.00	3.7 e+01	3.7 e+01	4.0 e+01
u (m/s) =	2	0.2	0	8	3	1.00	1.1 e+02	1.4 e+02	1.5 e+02
ASC =	F	0.4	0	16	6	0.99	5.3 e+01	9.3 e+01	1.0 e+02
H (m) =	5	0.7	0	27	9	0.99	2.2 e+01	4.2 e+01	4.5 e+01
Δt (min) =	30	1	0	38	12	0.98	1.2 e+01	2.4 e+01	2.5 e+01
z (m) =	1	2	0	73	20	0.97	4.0 e+00	7.9 e+00	8.5 e+00
Vs (cm/s) =	0.02	4	0	135	29	0.95	1.5 e+00	2.9 e+00	3.1 e+00
Vd (cm/s) =	0.06	7	0	215	36	0.93	7.3 e-01	1.5 e+00	1.6 e+00
Srce-Depl:	yes	10	0	283	40	0.91	4.9 e-01	9.8 e-01	1.1 e+00
Iterations =	100	20	0	462	46	0.86	2.5 e-01	5.0 e-01	5.4 e-01
Type =	rural	40	0	716	49	0.78	1.4 e-01	2.7 e-01	2.9 e-01
Cm (0% reflection)		1	0.1	38	12	0.98	3.9 e-01	7.6 e-01	8.2 e-01
Cm* (100% reflection)		1	0.2	38	12	0.98	1.3 e-05	2.5 e-05	2.7 e-05
ML (surface loading)		1	0.4	38	12	0.98	1.6 e-23	3.1 e-23	3.3 e-23

Case:	No. 5	x (km)	y (km)	Sig. y	Sig. z	Qx/Qp	Cm (mg/m^3)	Cm* (mg/m^3)	ML (mg/m^2)
Qp (g/s) =	77	0.1	0	11	8	0.99	2.5 e+01	4.6 e+01	4.9 e+02
u (m/s) =	5	0.2	0	22	16	0.99	6.8 e+00	1.3 e+01	1.4 e+02
ASC =	C	0.4	0	43	31	0.98	1.8 e+00	3.6 e+00	3.8 e+01
H (m) =	5	0.7	0	74	52	0.97	6.1 e-01	1.2 e+00	1.3 e+01
Δt (min) =	30	1	0	105	73	0.97	3.1 e-01	6.2 e-01	6.7 e+00
z (m) =	1	2	0	201	135	0.96	8.6 e-02	1.7 e-01	1.9 e+00
Vs (cm/s) =	0.02	4	0	372	239	0.95	2.6 e-02	5.2 e-02	5.6 e-01
Vd (cm/s) =	0.6	7	0	591	361	0.94	1.1 e-02	2.2 e-02	2.3 e-01
Srce-Depl:	yes	10	0	778	462	0.93	6.4 e-03	1.3 e-02	1.4 e-01
Iterations =	100	20	0	1270	716	0.92	2.5 e-03	5.0 e-03	5.4 e-02
Type =	rural	40	0	1968	1067	0.91	1.1 e-03	2.1 e-03	2.3 e-02
Cm (0% reflection)		1	0.1	105	73	0.97	2.0 e-01	3.9 e-01	4.2 e+00
Cm* (100% reflection)		1	0.2	105	73	0.97	5.0 e-02	1.0 e-01	1.1 e+00
ML (surface loading)		1	0.4	105	73	0.97	2.1 e-04	4.3 e-04	4.6 e-03

Case:	No. 6	x (km)	y (km)	Sig. y	Sig. z	Qx/Qp	Cm (mg/m^3)	Cm* (mg/m^3)	ML (mg/m^2)
Qp (g/s) =	77	0.1	0	11	8	1.00	3.7 e+01	6.4 e+01	6.9 e+01
u (m/s) =	2	0.2	0	22	16	1.00	1.5 e+01	2.9 e+01	3.2 e+01
ASC =	C	0.4	0	43	31	1.00	4.4 e+00	8.7 e+00	9.4 e+00
H (m) =	10	0.7	0	74	52	0.99	1.5 e+00	3.1 e+00	3.3 e+00
Δt (min) =	30	1	0	105	73	0.99	7.9 e-01	1.6 e+00	1.7 e+00
z (m) =	1	2	0	201	135	0.99	2.2 e-01	4.5 e-01	4.8 e-01
Vs (cm/s) =	0.02	4	0	372	239	0.99	6.8 e-02	1.4 e-01	1.5 e-01
Vd (cm/s) =	0.06	7	0	591	361	0.99	2.8 e-02	5.7 e-02	6.1 e-02
Srce-Depl:	yes	10	0	778	462	0.98	1.7 e-02	3.4 e-02	3.6 e-02
Iterations =	100	20	0	1270	716	0.98	6.6 e-03	1.3 e-02	1.4 e-02
Type =	rural	40	0	1968	1067	0.98	2.9 e-03	5.7 e-03	6.2 e-03
Cm (0% reflection)		1	0.1	105	73	0.99	5.0 e-01	1.0 e+00	1.1 e+00
Cm* (100% reflection)		1	0.2	105	73	0.99	1.3 e-01	2.6 e-01	2.8 e-01
ML (surface loading)		1	0.4	105	73	0.99	5.5 e-04	1.1 e-03	1.2 e-03

* Continuous generation, source-depleting, tilting plume, 0.1 km ≤ x ≤ 40 km.

The air concentrations predicted to occur for Cases 5 and 6 were within the ranges of those predicted for Cases 1 through 4 (Figure A.3). Case 5 (mean wind speed of 5 m/s) resulted in predicted air concentrations that were about 38% of those for Case 2. This is close to the scalar relationship described above (Cm' = Cm[u/u']), which would result in a concentration level that is 40% of that of Case 2. The difference between the two methods of calculation is caused by neglecting plume depletion in the scalar equation (plume depletion is enhanced by the fog oil deposition velocity being greater at 5 m/s than at 2 m/s). Case 6 (initial plume elevation of 10 m) yields identical air concentrations at distances greater than about 0.2 to 0.4 km downwind of the source. Closer to the source, the resulting near-ground-level concentrations for Case 6 are less than those for Case 2; this is because the plume released at 10 m (Case 6) travels a farther distance downwind before it first comes into contact with the ground. By comparing Cases 2 and 6 it can be seen that exact selection of initial plume height is not critical to successfully predicting plume dispersion characteristics.

Predicted fog oil surface deposition levels for Cases 1, 2, 3, and 4 (shown in Figure A.2) generally decreased from 30 - 800 mg/m^2 at a downwind distance of about 0.1 km, to less than 0.001 - 0.3 mg/m^2 at a distance of 40 km (Figure A.2). Within about 0.3 km of the source, the greatest levels of surface deposits were predicted for Case 3; at greater distances, the levels for Case 4 were greatest. Case 3 deposits are predicted to exceed those of Case 4 close to the source because of the limited atmospheric mixing of the plume (ASC F). Under those conditions, the plume does not come into contact with the ground as close to the source as it does for the other cases. In addition, the greater wind speed and deposition velocity assigned to Case 3 (5 m/s and 0.6 cm/s) contribute to greater predicted fog oil deposition near the generator than for the other cases. The greatest surface deposits are predicted within 0.1 km of the source for Cases 1 through 3. For Case 4, because of limited atmospheric mixing (ASC F), the greatest surface loading may occur between 0.1 and 0.4 km downwind of the source. As is the case for air concentration, the decrease in predicted surface mass loading with increasing downwind distance for Case 4 is less than that for the other cases. At comparable downwind distances, surface deposition level estimates for the test cases varied by factors of 27 to 260. The crosswind profiles (Tables A.4 and A.5) are widest for Case 1 (ASC A) and narrowest for Case 4 (ASC F). However, as is the case for the centerline plume deposition level estimates, crosswind estimates are likely to be conservative (too great) unless air flow is very uniform in direction. Actual areal estimates of the regions impacted will depend on the direction the wind blows. Where a unidirectional wind vector is common, these estimates may apply within perhaps 45° of the downwind direction (i.e., for a south wind, the impacted area may be expected to be approximately between northwest and northeast of the test site). Where bidirectional or multidirectional winds are common, the estimates will be generally conservative because the smokes will tend to be dispersed in more than one direction. In valley areas, concentrations and surface loadings may be highly localized. Site- and test-specific plans should consider this type of climate and terrain information. The maximum predicted surface mass loading was 800 mg/m^2 for Case 3 at a distance of 0.1 km downwind of the source. Greater loading rates are possible within 0.1 km of the source. Surface mass loadings exceeding 1 mg/m^2 were predicted within 0.7 to 10 km of the source, depending greatly on atmospheric conditions (Figure A.2). These results are based on a single 30-min release of fog oil smoke at 77 g/s (80 gal/h); neglecting evaporation and degradation of deposits, additional releases from a given site under roughly similar atmospheric conditions can be considered to have a scalar affect.

The surface deposition levels predicted to occur for Cases 5 and 6 were within the ranges predicted for Cases 1 through 4 (Figure A.4). Case 5 ($u = 5$ m/s, $V_d = 0.6$ cm/s) resulted in predicted surface deposition levels about 3.8 times greater than those for the comparable Case 2. This is close to the scalar relationship described above (ML' = ML[V_d'/V_d][u/u']), which would result in a surface deposition level 4.0 times greater than that of Case 2. The difference between the two methods of calculation is caused by neglecting plume depletion in the scalar equation (plume depletion is enhanced by the fog oil deposition velocity being greater at 5 m/s than at 2 m/s). Case 6 (initial plume elevation of 10 m) yields identical surface deposition levels at distances greater than about 0.2 to 0.4 km downwind of the source. Closer to the source, the resulting surface deposition levels for Case 6 are less than those for Case 2; this is because the plume released at 10 m (Case 6) travels farther downwind before it first comes into contact with the ground. As for air concentration, a comparison of Cases 2 and 6 shows that exact selection of initial plume height is not critical to successfully predicting plume dispersion characteristics.

Fog Oil Evaporation and Degradation:

The mass of fog oil particles in a cloud released from a smoke generator will decrease with time as a function of temperature as the fog oil particles evaporate. However, because of the low rate of evaporation (compared to the minutes or few hours of aerial transport prior to deposition) and because of the variation in temperatures at which testing may occur (desert to arctic), evaporation was not considered in the present model. By neglecting evaporation in the transport and deposition of fog oil aerosols, the present model provides conservative estimates of surface deposition levels. The evaporation rates of fog oil droplets (applicable only to windborne particles) are summarized here for use in predicting the possibility of evaporation influencing model results. This summary of fog oil evaporation is based on theory, and such predictions should be validated experimentally.

The significance of neglecting fog oil evaporation in the model calculations can be evaluated for a range of temperatures using the simple model given by Rubel (1991) to predict the evaporation time for fog oil drops. If Mo is the initial mass of a fog oil drop and M is the mass at time t after the start of evaporation, the evaporation time in seconds at an air temperature of 40°C (313 K), t40°C, is given by Equation (A.4).

$$t40°C = \frac{RTrd2\ [1 - (M/Mo)(2/3-b)]}{12\ DMw\ (100b)\ ea\ (2/3-b)} \qquad \text{(A.4)}$$

Evaporation times for other temperatures can be obtained using Equation (A.5).

$$t_T = t40°C\ (T/T40°C)\mathrm{exp}^{([-\Delta H/R][1/T40°C\ -\ 1/T])} \qquad \text{(A.5)}$$

where t_T = evaporation time for air temperature T (K)
R = universal gas constant (8.31×10^7 erg/mol-K)
r = density of fog oil (0.92 g/cm^3)
d = drop diameter (cm)
DMw = product of gas-phase diffusivity and molecular weight for fog oil
(DMw = 13.5 g-cm^2/mol-s)
b = an empirical constant (7.45)
a = an empirical constant (-33.48)
ΔH = latent heat of vaporization of fog oil (6.42×10^{11} erg/mol).

Table A.6 lists the partial evaporation lifetimes of a fog oil droplet with an initial diameter of 1.5 μm as determined from Equations (A.4) and (A.5) for ambient temperatures between +40 ° and -40°C. Inspection of the table indicates that, although as much as 70% of the mass of windborne fog oil could be evaporated within 1 h of release during tests in hot regions, only about 20% of the material might evaporate during tests under arctic conditions. Even under hot conditions, complete evaporation is not likely while the particles remain aloft. The time required for windborne fog oil particles to lose 90% of their mass by evaporation ranges from 15 days to 150 years as temperature decreases from +40 ° to -40 °C; all of these durations exceed the likely residence time of fog oil in the atmosphere. Thus, the degree to which the present model is conservative is related to the time-of-flight of the fog oil plume and to the temperature of the atmosphere, and if tests are performed above freezing, fog oil surface deposition levels could be 50 to 70% lower than those predicted. Such corrections are probably within the uncertainty of the model, and it is not recommended that temperature corrections be employed unless indicated to be cost effective in the initial assessment of a proposed smoke test.

Degradation processes affecting fog oil deposited to ground and other surfaces are not completely understood, but they are thought to include photodegradation and biodegradation. Degradative impacts on fog oil surface deposits and the related impact of incorporation of fog oil in surfaces or plants are discussed in the body of this assessment. Degradation of fog oil deposits was not included in the present model.

TABLE A.6. Lifetime of a Fog Oil Droplet Having an Initial Diameter of 1.5 µm, as a Function of Temperature (Driver et al. 1992).

Remaining Mass Fraction of Droplet (M/Mo)	Evaporation Time (ts), s				
	40 °C	20 °C	0 °C	-20 °C	-40 °C
1.00	0	0	0	0	0
0.90	2.22×10^{-1}	1.1×10^{0}	7.2×10^{0}	6.2×10^{1}	7.8×10^{2}
0.80	7.53×10^{-1}	3.8×10^{0}	2.4×10^{1}	2.1×10^{2}	$\underline{2.7 \times 10^{3}}$
0.70	2.17×10^{0}	1.1×10^{0}	7.1×10^{1}	6.1×10^{2}	7.7×10^{3}
0.60	6.58×10^{0}	3.3×10^{1}	2.1×10^{2}	$\underline{1.8 \times 10^{3}}$	2.3×10^{4}
0.50	2.32×10^{1}	1.2×10^{2}	7.5×10^{2}	6.5×10^{3}	8.2×10^{4}
0.40	1.06×10^{2}	$\underline{5.3 \times 10^{2}}$	$\underline{3.4 \times 10^{3}}$	3.0×10^{4}	3.7×10^{5}
0.30	$\underline{7.48 \times 10^{2}}$	3.8×10^{3}	2.4×10^{4}	2.1×10^{5}	2.6×10^{6}
0.20	1.17×10^{4}	5.9×10^{4}	3.8×10^{5}	3.3×10^{6}	4.1×10^{7}
0.10	1.29×10^{6}	6.5×10^{6}	4.2×10^{7}	3.6×10^{8}	4.6×10^{9}

The underlined evaporation times in each column represent the degree to which windborne fog oil particles are expected to be partially evaporated during a 1-h (3.6×10^{3} s) period following release.

Visibility Reductions Caused by Fog Oil Aerosols:

A final potentially significant atmospheric impact of fog oil smoke testing is the possibility that the smoke will cause visibility reductions that are hazardous for motor vehicle operations even beyond the boundary of the test site. The duration of a visibility reduction caused by smoke will vary with the duration and rate of fog oil smoke generation and with atmospheric conditions. Figure A.5 shows the light transmittances reported by Driver et al. (1992) for a test under arctic conditions using a mixed fog oil and graphite flake aerosol, over a 1-km crosswind view though the centerline of the smoke cloud calculated using DPG's HECSO smoke obscuration model (Dumbauld et al. 1981) and mass-extinction coefficients for fog oil and graphite of 6.85 and 1.5 m^2/g, respectively (Hoock et al. 1987). (The HECSO model uses the same diffusion model algorithms as RTVSM.) The cases are not similar to those discussed in this appendix; the cases for

Figure A.5 are shown in Table A.7. The input parameters differ from those of the six cases discussed in this document because different models were used in the calculations. The wide range of calculated transmittances illustrates the fact that the screening effectiveness of the cloud produced by a smoke generator is highly dependent on the meteorological conditions. Experience gained at Dugway Proving Grounds, Utah, suggests that a target is always obscured if the transmittance is less than or equal to 5%. The distance over which the calculated transmittance for the example shown in Figure A.5 is less than 5% ranges between ~ 0 and ~ 20 km and depends strongly on atmospheric conditions. The information presented in Figure A.5 is an example only; site-specific calculations of visibility are recommended when vehicle traffic within about 25 km of the test site might be affected.

For the example in Figure A.5, the visibility estimates were made considering only the mixed fog oil and graphite aerosol and neglecting any visibility reduction caused by naturally occurring fog or human-caused ice fog. The transmittances in Figure A.5 were calculated under the very conservative assumptions of no fog oil evaporation and no fog oil or graphite flake deposition.

TABLE A.7. Real-Time Volume Source [Dispersion] Model Meteorological Inputs for an XM56 Fog Oil and Graphite Flake Release under Arctic Conditions (Driver et al. 1992). These cases are not the same as those discussed elsewhere in this appendix.

	Value					
Parameter	Case # 1	Case # 2	Case # 3	Case # 4	Case # 5	Case # 6
10-m Wind Speed (m/s)	1.6	4.8	1.5	4.8	1.4	4.5
Net Radiation Index	-1,-2	-1,-2	0	0	1	1
Turbulence Intensity [a,b]						
Lateral	0.070	0.117	0.175	0.157	0.192	0.192
Vertical	0.052	0.082	0.061	0.087	0.070	0.093
Wind-Profile Exponent [a]	0.30	0.20	0.25	0.20	0.20	0.15
Mixing Depth (m)	26	96	26	96	26	96
Pasquill Stability Category [c]	E-F	D	D	D	D	D
Vertical Potential Temperature Gradient (°C/m)	0.05	0.05	0.02	0.02	0.01	0.01

---

[a] The RTVSM default values of the turbulence intensities and wind-profile exponent are assigned based on the 10-m wind speed and net radiation index. The 2-m wind speed is 1 m/s for Cases 1, 3, and 5 and 3.5 m/s for Cases 2, 4, and 6.

[b] Turbulence intensities are 10-min values.

[c] Not an RTVSM input; provided for information only.

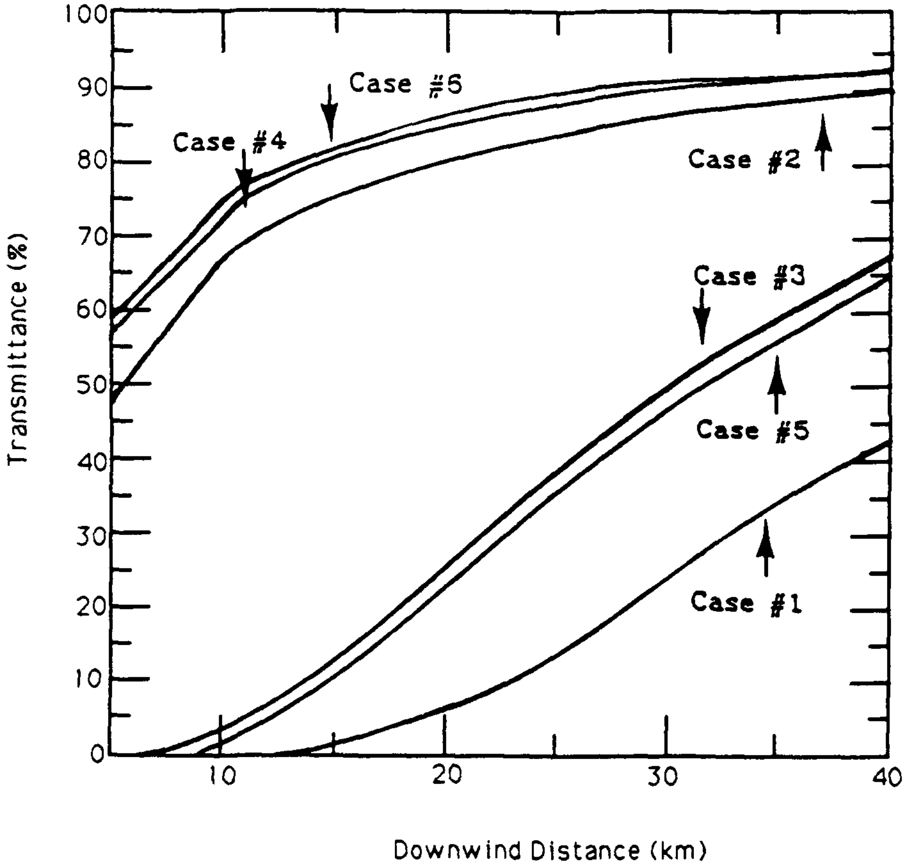

FIGURE A.5. Calculated Light Transmittances Over a 1-km Crosswind View Through the Centerline of the Smoke Cloud for Six Arctic Release Scenarios. See Table A.7 for a definition of the six scenarios. These cases are not the same as those discussed elsewhere in this appendix. (Driver et al. 1992)

APPENDIX A REFERENCES

Bjorklund, J. R. 1990. User Instructions for the Real Time Volume Source Dispersion Model (RTVSM) Version 3.00. TR-90-374-02, prepared by H. E. Cramer Company, Inc. for the U.S. Army Dugway Proving Ground, Dugway, Utah.

Briggs, G. A. 1973. Diffusion Estimation for Small Emissions. ATDL Contribution File No. 79, Atmospheric Turbulence and Diffusion Laboratory.

Cataldo, D. A., M. W. Ligotke, H. Bolton, Jr., R. J. Fellows, P. Van Voris, J. P. McKinley, S. W. Li, and K. M. McFadden. 1990. Transport, Transformations, Fate, and Terrestrial Ecological Effects of Brass Obscurants. Final Report, PNL-7459, Pacific Northwest Laboratories, Richland, Washington.

Cataldo, D. A., P. Van Voris, M. W. Ligotke, R. J. Fellows, B. D. McVeety, S. W. Li, H. Bolton, Jr., and J. K. Fredrickson. 1989. Transport, Transformations, Fate, and Terrestrial Ecological Effects of Fog Oil Obscurant Smokes. Final Report, PNL-6799, Pacific Northwest Laboratories, Richland, Washington.

Driver, C. J., M. W. Ligotke, J. F. Bowers, and E. B. Moore Jr. 1992. An Environmental Assessment of the Production Prove-Out Test of the XM56 Dual-Purpose Smoke Generator: Arctic Test Conditions, U.S. Army Cold Regions Test Center, Fort Greely, Alaska. Final Report, PNL-7984, Pacific Northwest Laboratories, Richland, Washington.

Dumbauld, R. K., S. F. Saterlie, and J. E. Rafferty. 1981. "A Dispersion-Optics Model for Calculating Visibility Impairment and Comparisons of Model Estimates with Field Measurements." Atmos. Environ. 15:2185-2196.

Gifford, F. A., Jr. 1976. "Turbulent Diffusion Typing Schemes. A Review." Nucl. Saf. 17:68-86.

Hanna, S. R., G. A. Briggs, and R. P. Hosker, Jr. 1982. Handbook on Atmospheric Diffusion. DOE/TIC-11223 (DE82002045), National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia.

Hoock, D. W., R. A. Sutherland, and D. Clayton. 1987. Combined Obscuration Model for Battlefield-Induced Contaminants (COMBIC). TR-022-11, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico.

Rubel, G. O. 1991. Persistency of Fog Oil Aerosol Under Arctic Conditions. Technical Note, Obscuration Sciences Branch, Research Directorate, U.S. Army Chemical Research, Development, and Engineering Center, Aberdeen Proving Ground, Maryland.

Van der Hoven, I. 1968. "Deposition of Particles and Gasses." In Meteorology and Atomic Energy - 1968, ed. D. Slade, pp. 202-208. TID-24190, U.S. Atomic Energy Commission, NTIS, U.S. Department of Commerce, Springfield, Virginia.

Wackter, D. J., and J. A. Foster. 1986. Industrial Source Complex (ISC) Dispersion Model User's Guide, Vol. 1, 2nd ed. EPA-450/4-86-005a, Source Receptor Analysis Branch, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Wark, K., and C. F. Warner. 1976. Air Pollution: Its Origin and Control. Harper & Row, Publishers, New York.