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An Assessment of the Impact of Fuel Jettisoning Events Using Simulation and Impact Models

Jeffrey M. Todd

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THESIS

Jeffrey M. Todd
Captain, United States Air Force

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THESIS

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Jeffrey M. Todd, B.E.

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Acknowledgments

Although I am not a mathematician, not a computer scientist, nor a meteorologist, I was somehow attracted to the subject of atmospheric transport modeling. As an environmental management student, I set out to find a topic which would allow me to refer to the management and engineering aspects of my academic program but also gain some insight into the more technical aspects of environmental science. I am thankful to the Engineering and Environmental Management department for allowing me to challenge myself with this topic.

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Jeffrey M. Todd

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Abstract

Due to emergency situations or urgent mission-essential operational requirements, aircraft may occasionally be required to jettison unused jet fuel. Work has been accomplished to determine the impact of the jettisoned fuel when it reaches the surface. While previous work has indicated that the jettisoning of JP-4 jet fuel results in a negligible ground fall impact, the impact of jettisoning the lower volatile JP-8 jet fuel has not been thoroughly characterized. Several efforts have been made to mathematically model the evaporation, advection, and dispersion of the plume of fuel as it travels to the surface. The AFIT Fuel Jettisoning Model, the Fuel Jettisoning Simulation Model, and the Fuel-Dumping Impact Assessment Model were evaluated and compared to assess the impact of jettisoning JP-8 jet fuel. Additionally, the AFIT Model has been modified to include surface evaporation to evaluate the time required to evaporate JP-8 jet fuel after it reaches the surface. This thesis has provided the following insight into the potential ground fall impact of JP-8 jettisoning. Concentrations of JP-8 jet fuel at the surface are an order of magnitude greater than concentrations of JP-4 jet fuel jettisoned under the same conditions. While JP-8 jet fuel does impact the surface more than JP-4 jet fuel, the mass of JP-8 jet fuel remaining from releases at altitudes equal to or greater than 6000 meters and at surface temperatures greater than 0°C can evaporate within hours. As jettisoning release heights exceed 6000 meters, the change in impact is negligible. We conclude that the recommended jettison release altitude for large body aircraft of 6000 meters is adequate.

AN ASSESSMENT OF THE IMPACT OF

FUEL JETTISONING EVENTS USING

SIMULATION AND IMPACT MODELS

I. Introduction

1.1 Background

Jet fuel jettisoning is an active and intentional release of unused fuel from an aircraft in flight. Jettisoning of jet fuel is warranted only during flight emergencies and urgent mission-essential operational requirements. The primary purpose of jettisoning is to reduce the weight of the aircraft and therefore decrease the possibility of accidents during landings (Quackenbush, et al., 1994:2751). In extremely rare situations, such as the loss of two engines on takeoff, fuel jettisoning may be implemented to increase climbout capability (Phillips, 1995). A study by the Air Force Engineering and Services Center of individual fuel jettisoning events reported by Air Force aircrews from 1 January 1975 to 30 June 1978 estimated that Air Force aircraft jettisoned fuel approximately 1000 times a year, totaling more than 16 million pounds per year (Clewell, 1980(a), 1980(b), 1983). However, current policy governing the conditions required to jettison fuel is much more restrictive than during the 1970s.

Current fuel jettisoning data is not formally or centrally maintained. However, policy and procedures have been implemented to minimize the frequency of fuel jettisoning. Air

Force Major Charles D. Phillips, Chief of the Training Integration Branch, Directorate of Operations, Air Mobility Command stated

> Fuel jettisoning is rarely accomplished. The C-5 and C-141 aircraft, for example, can safely land with maximum fuel loads. If a mission were to be terminated because of an inflight emergency situation, fuel jettisoning would not likely be employed. In fact, none of the C-141 instructor pilots on our staff had ever jettisoned fuel. Even in the KC-135, which does have a maximum landing weight, fuel jettisoning is infrequent, and is often discouraged because of potential environmental concerns and public pressure...In addition, from a crewmember's standpoint, fuel is time. There are very few emergencies that require an immediate landing, and increased fuel reserves "buy" extra time to troubleshoot the problem, discuss all the variables (weather, strange fields, crew fatigue, day/night conditions, etc.) and plan a recovery to the destination. (Phillips, 1995)

Therefore, the previous survey is useful for evaluating individual release characteristics such as fuel quantities, release altitudes, jettison rates, and other jettison data. However, the frequency of jettison events estimated during the 1970s may not be accurate for current activities. It is our assumption that fuel jettisoning is currently infrequent.

Current fuel jettisoning events are further regulated by flying operations procedures for each aircraft. Multi-Command Instruction 11-235, Volume 5 (Department of the Air Force, 1 July 1995), includes the fuel jettisoning procedures for the KC-135 air refueling aircraft. In addition to restating the conditions required to warrant fuel jettisoning, the instruction provides operational and administrative requirements. The aircraft operators are required to use designated jettison areas and are to use jettison altitudes above 20,000 feet (6000 meters) to the maximum extent possible.

The aircrew are required to record all data associated with the jettison event to include flight conditions, altitude, airspeed, air temperature, wind direction and velocity, type and amount of fuel, duration of jettison event, and the reason for jettisoning. This data is to be maintained by the aircraft's unit for six months. The aircraft unit will request an environmental impact analysis and provide the recorded data to the installation environmental office (Department of the Air Force, 1 July 1995). These procedures are essentially the same in flying procedures for each aircraft. The procedures for fuel jettisoning are in Appendix A.

The Federal Aviation Administration also provides guidance for fuel dumping incidents in FAA Order 7110.65J, Air Traffic Control, Chapter 9, Section 6 (Federal Aviation Administration, 20 July 1995). Air traffic controllers are required to determine the weather conditions and assign the location and altitudes at which fuel dumping operations will occur (Connor, 1995).

1.2 Specific Problem

Fuel jettisoned by aircraft in flight may pose an environmental hazard by reaching the surface and causing environmental contamination. Clewell concluded that if JP-4 jet fuel was jettisoned above a critical altitude of 20,000 feet (6000 meters), the ultimate ground fall and related environmental impact would be negligible. Therefore, minimum release altitudes were recommended for both fighter aircraft and large-body aircraft (Clewell, 1983:384). However, Clewell hypothesized that the jettisoning of JP-8 jet fuel from any altitude in the troposphere (less than twelve kilometers), because of its low volatility, would result in significant ground fall (Clewell, 1981:24).

The lower volatility of JP-8 jet fuel increases the time required for complete evaporation at ambient temperatures. While this characteristic reduces operational evaporative losses (Martel, 1987:11), it also increases the chance that jettisoned fuel will impact and contaminate the earth's surface. Therefore, the Air Force's conversion from JP-4 jet fuel to the less volatile JP-8 jet fuel has significantly increased the likelihood of ground fall during fuel jettisoning events. Other U.S. and foreign military services are also converting to JP-8 jet fuel or similar fuels and JP-8 jet fuel is the primary fuel for all NATO forces in Europe. Commercial aircraft use Jet Fuel A which is the commercial equivalent to JP-8 and will also behave similar to JP-8 if jettisoned from commercial aircraft.

The potential ground fall of jettisoned JP-8 jet fuel could significantly impact the operations of USAF aircraft both in the United States and in overseas theaters. Environmental regulations and public pressure could restrict the range of flight operations available to USAF aircraft if accurate characteristics of jettisoned JP-8 jet fuel is unknown. Additionally, if the likelihood of jettisoned JP-8 jet fuel ground fall is determined to be high, then the Air Force needs tools to predict the impact of and to respond to these ground fall events. Using accurate prediction models for ground fall, Air Force managers can predetermine optimum jettisoning altitudes and locations and prepare responses to adverse ground fall impacts.

1.3 Research Objectives

This research is sponsored by the Environics Directorate of the Armstong Laboratory, Tyndall Air Force Base, Florida. In addition to our work, Continuum Dynamics, Incorporated of Princeton, New Jersey is under contract with Armstong Laboratory to develop a fuel jettison simulation model to be used by Air Force organizations. Previously, ReJen Company of Bishop, California produced a fuel jettison impact model under contract for Armstrong Laboratory.

While research has been accomplished into various components of a computational model to predict the ground fall impact of jettisoned JP-8, the application of these computer models has not been fully evaluated. Therefore, the thesis evaluates the useability and applicability of these models. This thesis also evaluates the results of two fuel jettisoning simulation models and addresses the significance of possible JP-8 ground fall. Additionally, the thesis evaluates a new version of the AFIT Fuel Jettisoning Model which includes surface evaporation of the fuel to determine if fuel reaching the surface will continue to evaporate in a timely manner. Finally, we evaluate the prescribed jettison release altitudes for their adequacy.

1.4 Scope and Limitations

The research was accomplished by modifying the input data files for the AFIT Model. The coding of the central model was not modified. Only the calculations for surface evaporation of the jet fuel was added to the model and associated code. The surface evaporation equations are elementary and meant only to be an initial attempt to characterize the surface evaporative process. There are no changes to the physics or mathematics of the model nor to the chemical compositions of the fuel data files.

There is no consideration of chemical reactions in the atmosphere. Chemical reactions could results in significant environmental impact, but the study of those reactions are a subject of future work. Likewise, there is no study of the toxicity of the jet fuel concentrations in the atmosphere or at the surface. The model calculates concentrations in mass per area. The surface characteristics would have to be known before toxicity or regulatory concentration levels in parts per million could be characterized.

The primary limitation of this thesis is the lack of current data on jet fuel jettisoning. Many of our assumptions must be made using previous survey data and by information from current aircrew members. Likewise, the lack of current experimental data on the physics incorporated in the model force us to accept the findings and assumptions of previous work.

1.5 Overview

Fuel jettisoning simulation models have been developed to predict and characterize the impact of jettisoned fuel at the surface. This thesis evaluates these models for application to JP-8 jet fuel releases. Chapter II provides background into previous research involving jet fuel jettisoning and associated topics. Chapter III presents the approach we implemented to evaluate the models and an extension to the AFIT Model to characterize surface evaporation of the fuel. Chapter IV presents the results of our parameter study and our analysis of surface evaporation of the jet fuel. Chapter V presents a summary of the research, our conclusions, and recommendations for further research. Appendix A presents the excerpt from MCI 11-235, KC-135 Flying Operation, that provides procedures for fuel jettisoning. Appendix B presents the fuel component models of JP-4 and JP-8 used by the AFIT Model. Appendix C presents sample AFIT Model results in the format produced by the model.

II. Background

2.1 Introduction

To determine the significance of the ground fall impact of jettisoned JP-8 jet fuel, we must be able to characterize and simulate the physical processes the jet fuel encounters as it makes its way to the surface. When jettisoned, jet fuel breaks up into small droplets and begins to evaporate. As the fuel continues to evaporate, it is moved by the forces of wind and gravity. The wind also influences the dispersion of the fuel plume. Therefore, research in the area of fuel droplet size distribution and evaporation is significant. Likewise, knowledge of dispersion characteristics of jet fuel in the atmosphere is also required. This chapter will review work accomplished in the area droplet size distribution as well as evaporation. Finally, this chapter will summarize work accomplished in the area of fuel jettisoning simulation modeling.

2.2 Droplet Size Distribution

Research into the initial droplet size distribution of the fuel plume has been conducted to characterize the initial conditions of the plume. Cross and Picknett (1973) conducted field experiments to characterize to initial droplet distribution of JP-4 and JP-8. Fluorescent-tagged fuel was jettisoned at a rate of 450 kilograms per minute from an aircraft flying at an altitude of 15 meters with an airspeed of 120 meters per second. The droplet distribution was collected on photographic filter paper. Using data from a port parallel with the airstream, Cross and Picknett found the mass mean diameter to be 270 micrometers (Cross and Picknett, 1973).

Wasson and colleagues at the Arnold Engineering and Development Center (AEDC) conducted a series of wind tunnel experiments from 22 October 1973 to 12 December 1973 to study initial droplet distributions. The wind tunnel experiments were conducted for velocities from 200 to 400 knots, altitudes from 12,000 to 25,000 feet, and jettison rates from 13 to 290 pounds per minute. Wasson concluded that diameter of jettisoned JP-4 droplets should be in the range of 19 to 36 micrometers. The maximum diameter reported was 100 micrometers (Wasson, 1975).

Noting the disagreement between Cross and Picknett and Wasson, Dawbarn, also at AEDC, proposed that the experimental methods used could account for the differences. Cross and Picknett had sampled away from the jettison port (at least 15 meters) and had used realistic jettison rates. Wasson, on the other hand, sampled nearer the jettison port and was restricted to the wind tunnel generated jettison rates. Dawbarn measured droplet sizes both near and away from the jettison port and found agreement with both studies. He concluded that smaller droplets found near the jettison port drifted away from the plume while larger droplets continued to be advected away from the jettison port as part of the fuel plume (Dawbarn, 1975).

Clewell conducted additional research into the distribution of droplet sizes. Clewell arranged for a sampling aircraft to follow a KC-135 aircraft as the KC-135 was jettisoning fuel at rate of 56 kg/s and an airspeed of 170 m/s. The sampling aircraft was approximately

90 seconds behind the KC-135 and therefore sampled data 90 seconds after the jettison event. Sampling was also performed at the ground to determine the impact of jettisoned fuel to the surface. To interpret the data from the experiment, Clewell developed an evaporation model based on Lowell's work. Using this model, Clewell estimated that the droplets had lost more than 80% of its original mass within the 90 seconds before the second aircraft sampled the droplets. Using the data from the experiment, he interpolated backwards to calculate an initial mass median diameter of 270 micrometers (Clewell, 1980 (c):31). This result was in excellent agreement with Cross and Picknett.

2.3 Evaporation

The evaporation of multicomponent fuel droplets has been previously investigated primarily to better understand combustion (Renksizbulut and Bussmann, 1993). However, observations made during these studies can be successfully applied to the study of evaporation of free falling fuel droplets in the atmosphere. Chin and Lefebvre studied the evaporation of hydrocarbons and calculated several evaporation constants for JP-4 and other aviation fuels. Their numerical solutions for the evaporation constants of JP-4 jet fuel compared well with published experimental data (Chin and Lefebvre, 1983).

In contrast to the simplified assumptions used by Clewell (1980 (c)) and others, Renksizbulut and Bussmann developed a very detailed model of multicomponent evaporation using numerical methods. They also noted that fuel components do not always evaporate sequentially from the most volatile to the least volatile. This is due to the possibility of more volatile fuel components remaining in the core of the droplet while less volatile components are at or near the surface of the droplet. They state that liquid phase mass diffusion occurs very slowly and therefore reduces the speed with which the more volatile components reach the surface of the droplet. Evaporation is then influenced not only by "component volatility, but also by the rate of species diffusion and droplet surface regression, as well as the nature of fluid motion within the droplet" (Renksizbulut and Bussmann, 1993). Another related phenomena that was studied by Renksizbulut and Bussmann was the possibility of a micro-explosion caused by the evaporation of volatile components at the surface which are not replace immediately from the interior of the droplet The remaining less volatile components at the surface cause an increase to the surface temperature of the droplet and can lead to micro-explosions or droplet fragmentation (Renksizbulut and Bussmann, 1993).

2.4 Fuel Jettisoning Models

The dispersion and evaporation characteristics and effects of JP-4 jet fuel and other aircraft fuels have been studied and correlated with the acquisition and refinement of various dispersion and evaporation modeling techniques. The evolution of fuel jettisoning simulation models evaluated as part of this thesis come from two distinct approaches. The AFIT Model is a result of research extending the work begun in the 1950's and continuing through the next three decades (Lowell, 1959; Clewell, 1983; Pfeiffer, 1994). Likewise, the Fuel-Dumping Impact Assessment Model is an independent product extending the research by Lowell and Clewell (Ferrenberg, 1993). The developers of the Fuel Jettisoning Simulation Model acknowledge the work by Lowell and Clewell but extend research into aerial pesticides application and apply that knowledge to the jettisoning of fuel from aircraft (Quackenbush, et al., 1994).

2.4.1 Lowell, 1959

Lowell was one of the first researchers to specifically address the impact of jettisoned jet fuel. He first developed free fall and evaporation equations for JP-4 jet fuel droplets in a quiet atmosphere. He simplified the composition of JP-4 jet fuel by using a 10 component model with specified physical and chemical properties (Lowell, 1959 (a):3). The major assumptions stated by Lowell were:

(1) Each droplet falls in isolation from other droplets. Lowell does note that this assumption will result in falling speeds of the droplet being, initially, too low (1959 (a):2).

(2) Evaporated molecules are immediately removed from the system. Lowell commented that this assumption may result in the overestimation of evaporation. However, Dawbarn concluded that the evaporated molecules had a negligible effect on the terminal velocity of the droplets (Dawbarn, 1975:35).

(3) Each droplet is always at its terminal velocity. Over the time scale of the model, any slight accelerations and decelerations would be negligible.

(4) The droplet temperature is uniform and equal to the ambient temperature. Lowell stated that this assumption was made to increase the speed of computation of the model and

that, except for high ambient temperatures and small droplet sizes, the results were not significantly affected.

Lowell's model consisted of two primary components: a free fall model and an evaporation model. The free fall model was written to determine the change in altitude of a droplet as a function of time and the droplet's terminal velocity. The evaporation model simultaneously calculated the evaporation rate and the mass evaporated from the droplet based on the droplet's velocity and temperature. The change in mass and the ambient temperature as a function of the altitude using the standard atmosphere, were then included in the free fall model at the next time interval (Lowell, 1959 (a):9-13). He concluded that temperature was the principle controlling factor in the calculation of evaporation rates (Lowell, 1959 (a):1).

In a separate study, Lowell developed a dispersion model of jettisoned JP-4 jet fuel to assess the flammability of the jettisoned fuel. In this investigation, he neglected "early dispersal phenomena," and assumed a plume of jettisoned fuel similar to an infinite, instantaneous line source (Lowell, 1959 (b):7). His model then combined the free fall and evaporation effects of his previous work with the dispersion model into a more complete model of the fate of jettisoned JP-4 jet fuel. Lowell restricted his analysis and conclusions to the flammability hazards associated with the dispersion of the fuel. However, he did acknowledge the "possibility that ground contamination is of importance, from the point of view of creation of both nuisances and fire-hazardous conditions" (Lowell, 1959 (b):3).

2.4.2 Clewell, 1980

Clewell undertook a comprehensive effort to characterize the dispersion and evaporation of jettisoned JP-4 jet fuel from 1972 to 1980. By request of the Environics Branch, Air Force Regulation 19-3 (now rescinded) required all noncombat fuel jettisoning events to be reported to include all pertinent information. Clewell's summary and analysis of these records provided insight into the frequency and characteristics of jettisoning events (Clewell, 1980 (a), 1980 (b)).

Clewell used Lowell's work as a basis for further research to better understand the drop formation and evaporation of JP-4 jet fuel jettisoned from aircraft in flight (Good and Clewell, 1983:452). Clewell expanded Lowell's 10-component model to a 33-component model which was more representative of JP-4. He also used the temperature of the aircraft tanks as the initial temperature of the droplets rather than the ambient temperature (Clewell, 1980 (c):86). Clewell's model follows a droplet through a series of time intervals. The distance the droplets falls during each interval is calculated at a constant terminal velocity for its current diameter, density, and altitude. Loss of mass through evaporation is calculated assuming Raoult's law; which states that each component evaporates independently. At each time interval, the droplet temperature is adjusted using an energy balance to allow for evaporative cooling, radiation, conduction, and insolation effects. The new droplet composition, mass and altitude are then used as the initial values for the next time interval. These calculations are continued until the droplet reaches the surface or until the loss of 99.9% of the initial mass of the droplet (Clewell, 1980 (c):4).

Clewell used this model to compare the effect of different fuels on the potential for ground fall from a jettison event. In addition to his JP-4 jet fuel model, Clewell developed a 27-component model of JP-8 jet fuel. Clewell's research indicated that for jettisoning events as low as 750 meters above the ground at temperatures around 11°C, no liquid JP-4 jet fuel could be detected by ground observers and no significant hydrocarbon concentrations were measured(Clewell, 1980(c):45). Clewell concluded that for JP-4 jet fuel jettisoned above 1500 meters at surface temperatures greater than 0°C, more than 98% of the fuel should evaporate before reaching the surface and the impact of the remaining concentration of fuel would be insignificant. While ground fall from a jettison of JP-4 was negligible, he found that for surface temperatures below 0°C, a JP-8 jet fuel jettison event would result in approximately 20% of the fuel reaching the surface (Clewell, 1981:24).

2.4.3 Ferrenberg, 1993

Ferrenberg developed the Fuel-Dumping Impact Assessment Model (FDIAM) under contract by Armstrong Laboratory. Ferrenberg acknowledges the work of Clewell and others as the basis for his work. Many of FDIAM's subroutines are taking from Clewell. Apart from Clewell's work is an attempt by Ferrenberg to optimize the user interface and ease-of-use of the model. The following are computational assumptions made by FDIAM (Ferrenberg, 1993:5):

(1) The aircraft jettison flight profile can be separated into individual segments, each having a constant velocity, altitude, and direction.

(2) The wind velocity and direction do not change during the time required for jettisoning and settling. Wind velocity and direction do vary with altitude.

(3) The jettison rate is constant.

(4) The ground altitude remains constant during the jettison event

Ferrenberg, due to improved computational facilities, choose to relax several of the previous assumptions. Instead of using the stagnation temperature of the aircraft as the initial temperature, FDIAM calculates the temperature based on the aircraft's altitude and flight duration at the time of the jettisoning event. Ferrenberg also chose to not assume that the droplets are always at their terminal velocity and reasoned that the model should compute the evaporation and movement of the droplet at their creation (Ferrenberg, 1993:12).

Droplet movement and evaporation is modeled in essentially the same method as Clewell and others. However, Ferrenberg implemented a unique dispersion model. Instead of a standard dispersion model, Ferrenberg divides the flight profile of the aircraft into a series of straight line, constant altitude, segments. Ferrenberg assumes that each point along the line will be subject to identical forces and conditions as any other point. Therefore, instead of calculating the dispersion of the entire plume, FDIAM computes the advection and evaporation of a single "packet" of fuel and at ground fall, establishes the deposition of all other packets released during the jettison event (Ferrenberg, 1993:1).

2.4.4 Quackenbush, et al., 1994

Another model, the Fuel Jettisoning Simulation Model (FJSIM) is under development by Continuum Dynamics, Incoporated (CDI) as part of an ongoing contract with Armstrong Laboratory's Environics Directorate. FJSIM combines and implements mathematical models for Lagrangian aircraft wake affects, Gaussian line source dispersion, droplet evaporation, and ground deposition to predict the fate of jettisoned JP-8 jet fuel (Quackenbush, et al., 1994:2752). FJSIM builds on previous research in the area of aerial pesticide spray application modeling.

The USDA Forest Service selectively uses aerial spray applications to control forest pests and the U.S. Army is interested in using spray applications for defensive strategies. Teske states that these agencies want to understand the "behavior of spray material from the time the spray is released from the aircraft until it is deposited or, in the case of spray drift, diffused to concentration/dosage levels that are environmentally insignificant" (Teske, et al., 1993).

Williamson and Threadgill proposed studying spray drift and spray droplet dynamics through mathematical modeling as an alternative to field tests. By using mathematical models, all variables could be controlled as opposed to the many uncontrollable variables in the field. They stated that the simulation of an agricultural spraying operation must consider simultaneously the three-dimensional droplet motion and the rate of mass transfer from the droplet due to evaporation. They also recognized that air motion must be included in the model. The model developed by Williamson and Threadgill simulate the droplet motion and evaporation for a single isolated droplet. The model was validated by measuring water droplet dynamics in a low-speed wind tunnel. They concluded that their model accurately predicted the horizontal and vertical movement of the droplets as well as the droplet diameter (Williamson and Threadgill, 1974).

The AGDISP (AGricultural DISPersal) model is based on a Lagrangian approach to the solution of the equations of motion of the released materials and includes simplified models for the aircraft wake and ambient turbulence effects. The AGDISP model tracks the motion of a group of droplets released from specified nozzle locations and treats the group as a spray droplet cloud. The dispersion of the droplets is calculated as the spray droplet cloud descend toward the ground surface. The local fluid velocities and the turbulent fluid fluctuations through which the droplets pass determine the accuracy of the AGDISP model (Bilanin, 1989).

FSCBG (Forest Service, Cramer, Barry, and Grim) is a Gaussian line-source model that takes the near-wake results of AGDISP and predicts the downwind dispersion and includes evaporation, meteorology, canopy penetration, and ground and canopy deposition factors. Version 3 of FSCBG is a modification of existing code for use on a personal computer (Rafferty and Bowers, 1993). FSCBG incorporates an analytical dispersion model for multiple line sources oriented in any wind direction, an evaporation model for volatile spray components, and a canopy penetration model for forest canopy interception. The FSCBG model requires input data on meteorology, aircraft characteristics, nozzle specifications, spray material characteristics, canopy information, and flight path information and then performs calculations with respect to meteorology, evaporation, canopy characteristics, near-wake, and dispersion (Teske et al, 1993).

Rafferty and Bowers point out that FSCBG Versions 2 and 3 use the AGDISP algorithms to predict spray behavior while the dominant effect is from the aircraft wake. The original FSCBG algorithms are used when the atmospheric diffusion processes become dominant. However, Rafferty and Bowers conducted several field trials comparing deposition measurements to FSCBG using (a) no wake effects, (b) the simple wake effects of the original model, and (c) the AGDISP complex wake effects of Version 3 and found little statistical evidence that the AGDISP algorithms improved the model (Rafferty and Bowers, 1993).

FJSIM retains a substantial portion of the near-wake AGDISP and the downwind dispersion FSCBG code (Quackenbush, et al., 1994:2752). The principle modification was to replace the water-based evaporation model with a multicomponent evaporation model applicable to hydrocarbon fuels. In concluding their description of the model in *Atmospheric Environment*, Quackenbush states

> Several analytical and computational tasks must be undertaken to enhance the capabilities of the model. These include implementation of time-varying meteorology, verification of JP-8 component evaporation rate and Law's multicomponent model in this application, and determination of the most appropriate droplet distribution. (Quackenbush, et al., 1994, p. 2756)

Additionally, the model has been developed for the Microsoft Windows environment with a user-friendly graphical interface which allows easy modification of input data.

2.4.5 Pfeiffer, Quinn, and Dungey, 1994

The AFIT Model consists of three distinct components; the environmental model, the evaporation and advection model, and the dispersion model. Because we utilize this model as our primary research tool, we will present a detailed description for completeness (Pfeiffer, 1994).

2.4.5.1 Environmental Model. The environmental model maintains the meteorological data for the other two components. However, the environmental model is not time-sensitive and therefore is considered constant throughout the model time scale. Pressure, temperature, and wind data are provided in the environmental data file. However, density, viscosity, and values for temperature and pressure at altitudes not provided in the environmental data file are calculated when required.

A temperature, T, at altitude z, assuming z is within the boundaries of the environmental data file, can be determined using the temperature lapse rate, Γ.

$$T = T_{known} - \Gamma(z - z_{known}) \tag{2.1}$$

A pressure, P, at altitude z is calculated using a form of the scale height equation for a hydrostatically balanced atmosphere (Hess, 1959:83 and Clewell, 1980(c):86):

$$P = P_{known}\left(\frac{T}{T_{known}}\right)^{\frac{gM_a}{\Gamma R_0}} \qquad (2.2)$$

where

g = acceleration due to gravity = 9.81 m/s^2

M_a = molecular weight of air = 28.96 kg/kmol

R_0 = universal gas constant = 8314 (N · m) / (K · kmol)

Density, ρ, is calculated assuming air is an ideal gas:

$$\rho = \frac{PM_a}{R_0 T} \qquad (2.3)$$

The kinematic viscosity, μ, is calculated using a relation published in the *U.S. Standard Atmosphere* (1976):

$$\mu = \frac{1.458 \cdot 10^{-6} T}{110.4 + T} \qquad (2.4)$$

where T is in Kelvin. The units of μ are $kg \cdot m^{-1} s^{-1}$ (Pfeiffer, 1994:3-7).

2.4.5.2 Evaporation and Advection Model. The evaporation and advection model uses a single droplet to characterize the evaporation and advection of the entire plume of jettisoned fuel. This single droplet is assumed to be at the center of the plume. The model uses a time step scheme at which each iteration of the model begins with an estimated time step Δt. At each iteration the change in altitude, Δz, and the change in droplet position, Δx and Δy, are calculated along with the change in mass due to evaporation, Δm, and change in droplet temperature, ΔT. The droplet characteristics are updated and any appropriate scaling is adjusted. If the droplet has not reached ground fall of has not completely evaporated (> 0.1 % of the original mass), the model advances to the next time step interval (Pfeiffer, 1994:3-8).

The initial droplet characteristics are provided in the input data files. The model assumes the initial chemical composition provided by the fuel data file and designated by the model initialization file. The initial altitude is assumed to be equal to the release altitude. The initial droplet temperature is assumed to be the stagnation temperature of the droplet with respect to the aircraft fuel tank. The stagnation temperature is calculated with the following equation derived from Holman (1976:152-153):

$$T_s = T_a \left(1 + \frac{(\gamma - 1)V^2}{2C_s^2} \right) \tag{2.5}$$

where

T_a = air temperature in Kelvin

V = aircraft airspeed

C_s = local speed of sound

$\gamma = \frac{C_p}{C_v} = 1.399721$

C_p and C_v are the specific heat of air at constant pressure and constant volume. Taking $(\gamma - 1)/2 \approx 1/5$, the equation is simplified to:

$$T_s = T_a \left(1 + \frac{V^2}{5C_s^2} \right) \tag{2.6}$$

which is the equation used by Clewell (1980(c):87). The local speed of sound is calculated with (Holman, 1976:153):

$$C_s = 20.045 \sqrt{T_a} \tag{2.7}$$

This equation is also consistent with Clewell (1980(c):87). The evaporation equations used by the AFIT Model are based on many of the assumptions made by Clewell, Lowell, and Dawbarn. The change in mass, Δm, is calculated by summing the changes in mass of the individual components:

$$\Delta m_i = \pi D^2 h_{m,i} p_i \epsilon_i \Delta t \tag{2.8}$$

where

m_i = mass of the i'th component of the droplet

D = droplet diameter

$h_{m,i}$ = mass transfer coefficient of the i'th component

p_i = vapor pressure of the i'th component

ϵ_i = mole fraction of the i'th component

This equation is derived from Lowell (1959:13) and Clewell (1980(c):88). The updated density, ρ_i, is calculated using Clewell (1980(c):87). The updated volume of the droplet is calculated by summing over the n components of the fuel mixture:

$$V = \sum_{i=1}^{n} V_i = \sum_{i=1}^{n} \frac{m_i}{\rho_i} \tag{2.9}$$

Before the droplet reaches ground fall, the model assumes the droplet is a perfect sphere where

$$V = \frac{4}{3}\pi r^3 \tag{2.10}$$

Substituting Equation 2.10 into Equation 2.9 and solving for r yields:

$$r = \sqrt[3]{\frac{3}{4\pi} \sum_{i=1}^{n} \frac{m_i}{\rho_i}} \tag{2.11}$$

Additionally, the model uses the change in mass, Δm, to compute the heat balance and the change in droplet temperature, ΔT (Pfeiffer, 1994:3-12).

Advection is addressed in the model by assuming the droplet begins with the speed of the aircraft and decelerates into the mean wind speed. Pfeiffer derived the relationship between the velocity of the droplet and the wind speed such that the velocity of the droplet approaches the wind speed as time approaches infinity. The droplet velocity, V, due to this initial deceleration is calculated with the following equation (Pfeiffer, 1994:3-14):

$$V = U - \frac{U - V_0}{1 + \frac{3}{8}\frac{\rho}{\rho_d}\frac{1}{r}C_d(U - V_0)^2 t} \tag{2.12}$$

where

U = mean wind speed

V_0 = initial airspeed

ρ = density of air

ρ_d = droplet density

C_d = drag coefficient

The droplet drag coefficient, C_d, is a function of the Reynolds number, Re, and is calculated by the following relationship suggested by Bilanin (1989) and Teske (1993) and originally developed by Langmuir and Blodgett:

$$C_d = \frac{24}{Re}(1 + 0.197Re^{0.63} + 2.6\cdot 10^{-4}Re^{1.38}) \quad (2.13)$$

The Reynolds number, *Re*, is (Holman, 1976:149):

$$Re = \frac{\rho V_{rel} D}{\mu} \quad (2.14)$$

where

V_{rel} = velocity of the free-stream fluid flow

μ = kinematic viscosity of the fluid

D = droplet diameter = characteristic length for a droplet

After the droplet is in the mean wind flow, its movement is simply computed using the component wind speeds and Δt.

2.4.5.3 Dispersion Model. The dispersion model implemented by the AFIT Model utilizes the entire jettison plume as its frame of reference. For simplification, the plume length is along the *x*-axis and the plume width is along the *y*-axis using a Gaussian distribution with:

$$\sigma = \frac{\text{plume width}}{3} \quad (2.15)$$

The distribution along the x-axis is uniform except for the ends (10% of total plume length) which are adjusted to "ramp up" and "ramp down" to provide for a smooth numerical solution (Pfeiffer, 1994:3-17). These initial conditions are similar to initial conditions for Gaussian line source solutions.

The primary equation used to model the concentration of fuel over the grid of interest is (Pfeiffer, 1994:3-17):

$$\frac{\partial c}{\partial t} = K_x \frac{\partial^2 c}{\partial x^2} + K_y \frac{\partial^2 c}{\partial y^2} \tag{2.16}$$

where c is the mean concentration and K_x and K_y are the eddy diffusion coefficients (Seinfeld, 1986:527). Two different techniques are then employed to calculate a numerical solution to this equation. An iterative Fourier series solution is first implemented and then a finite difference solution is implemented to verify the results of the Fourier technique.

Using Equation 2.16 the model assumes the following boundary and initial conditions:

$$c(x,y,0) = p(x)q(y)$$

$$c(x,y,t) \rightarrow 0 \text{ as } x,y \rightarrow \pm \infty$$

These initial conditions can be used to separate Equation 2.16 into two partial differential equations:

$$\frac{\partial f}{\partial t} - K_x \frac{\partial^2 f}{\partial x^2} = 0 \tag{2.17}$$

where

$$f(x,0) = p(x)$$
$$f(x,t) \rightarrow 0 \text{ as } x \rightarrow \pm \infty$$

and

$$\frac{\partial g}{\partial t} - K_y \frac{\partial^2 g}{\partial y^2} = 0 \tag{2.18}$$

where

$$g(y,0) = q(y)$$
$$g(y,t) \rightarrow 0 \text{ as } y \rightarrow \pm \infty$$

Noting that Equation 2.17 and Equation 2.18 are similar, we will address only $f(x)$ in the following description.

To develop the Fourier solution to Equation 2.17, the initial and boundary conditions are transformed to:

$$f(x,0) = p(x) \text{ for } 0 < x < L$$
$$f(0,t) = f(L,t) = 0$$

The Fourier solution is then:

$$f(x,t) = \sum_{n=1}^{\infty} A_n \sin\left(\frac{n\pi x}{L}\right) \exp\left(\frac{-K_x n^2 \pi^2}{L^2} t\right) \tag{2.19}$$

where

$$A_n = \frac{2}{L}\int_0^L p(x) \sin \frac{n\pi x}{L} dx \tag{2.20}$$

This iterative solution uses m time steps such that $m\Delta t$ equals the total time of descent. At each time step, new Fourier coefficients are calculated to integrate Equation 2.20 over the grid, assigning $f(x)$ to the next time step's $p(x)$. Zero-concentration boundary conditions are maintained by monitoring the plume dimension to grid length ratio, or solution creep. If the ratio threshold of 0.67 is exceeded, the grid will expand to ensure the zero boundary conditions (Pfeiffer, 1994:3-20).

The Fourier solution is verified with a finite difference solution. Pfeiffer uses a first-order forward-difference approximation to the time derivative (i subscript) and a second-order center-difference for the space derivative (j subscript) which is presented here explicitly for $c_{i+1,j}$:

$$c_{i+1,j} = c_{i,j} + \frac{K_x \Delta t}{\Delta x^2} (c_{i,j+1} - 2c_{i,j} + c_{i,j-1}) \tag{2.21}$$

The stability condition for Equation 2.21 is:

$$\Delta t \leq \frac{\Delta x^2}{2K_x} \tag{2.22}$$

By satisfying this stability condition, the scheme is second-order accurate in both time and space (Pfeiffer, 1994:3-20).

The eddy diffusion parameters, K_x and K_y, are calculated using the wind data provided by the user in an environmental data file. The equations, derived from Zannetti (1990:128), are:

$$K_x = \frac{10^3 \Delta\theta^2 u \mid \cos(\phi - \theta) \mid}{2} \tag{2.23}$$

and

$$K_y = \frac{10^3 \Delta\theta^2 u \mid \cos(90° - \phi - \theta) \mid}{2} \tag{2.24}$$

where

u = mean wind speed in m/s

ϕ = release heading of aircraft

θ = mean wind direction

and

$$\Delta\theta = \sigma_\theta + \sigma_\theta' \qquad (2.25)$$

where

σ_θ = standard deviation of the horizontal wind in radians

σ_θ' = $\pi \exp(-0.367 u)$ = uncertainty estimation

The uncertainty estimation is included to account for the possible absence of wind variability (Pfeiffer, 1994:3-21).

This concludes the summary of previous work in the area of simulation modeling of jettisoned fuel. The next chapter addresses our approach to assessing the fuel jettisoning simulation models and analyzing the significance of the impact of jettisoning JP-8 jet fuel.

III. Approach

3.1 Introduction

To determine the significance of JP-8 contamination at ground fall, we use two different models: the AFIT Model and the Fuel-Dumping Impact Assessment Model. The Fuel Jettisoning Simulation Model was not available for use during this thesis effort. The AFIT Model is used in a parameter study which consists of varying the input variables for both JP-4 jet fuel and JP-8 jet fuel cases. In addition to presenting the methods used to evaluate the significance of JP-8 contamination, this chapter will further describe the AFIT Model and present sample input files. Results from the AFIT Model are also compared to results generated by the Fuel-Dumping Impact Assessment Model (FDIAM). The models, although based on Clewell's previous work, were developed independently. Comparison of these results, generated by similar input values, provides additional credibility to the models' assumptions and calculations. Finally, equations for evaporation on the surface are proposed and evaluated.

3.2 AFIT Model Parametric Studies

The AFIT Model was used as our primary research tool. The model is freely available via anonymous Internet FTP to *archive.afit.af.mil* in the directory */pub/kpfeiffe*. The code is set up to run in the UNIX environment, however, the code can be compiled with available C compilers to run in a DOS environment. The model allows the user to vary jettison data, atmospheric data, fuel characteristics, and specify output files. Various jettison cases were run on the model to evaluate the impact of these input characteristics on the ground fall contamination and dispersion.

3.2.1 User Input Requirements.

The following figures are extracted from Pfeiffer (1994) and are included to ensure completeness of the discussion of the input requirements of the AFIT Model. Figure 3.1 describes the components of the *model.ini* initialization file. This file is the master file for each model case. The initialization file is executed by the command **model** *case.ini*, where **model** is the executable filename and *case.ini* can be any descriptive filename with the *ini* suffix. The initialization file also designates the output filenames. The message file, *case.msg*, contains evaporation and advection information at each time step of the model execution. The grid data output file, *case.grd*, receives concentration data relative to a generic grid. The map data output file, *case.map*, receives concentration data relative to latitude and longitude input values in the jettison data file (Pfeiffer, 1994: B-1).

file: model.ini

DESCRIPTION

This is the initialization file for the model. The name model.ini is arbitrary; this file name is supplied to the model executable on the command line.

Mandatory fields are:

jettison_data= (the jettison data file name)
environmental_data= (the environmental data file name)
fuel_data= (the fuel data file name)

Optional but recommended fields are:

output_messages= (message and model output file)
output_grid= (grid data output file)
output_map= (map data output file)

If the optional fields are not specified, default file names are assigned to these files. The message file is intended for tracing information (e.g. What are Kx and Ky at each iteration?) and warning messages. Critical error messages are always directed to the console.

Sample: kc135.ini	jettison_data=kc135.dat environmental_data=dayton.atm fuel_data=jp4.dat output_messages=kc135.msg output_grid=kc135.grid output_map=kc135.map

Figure 3.1 Sample *model.ini* File and Variable Description (Pfeiffer, 1994: B-2)

The atmospheric data used by the AFIT Model is provided by the environmental data file. The environmental data file is presented in Figure 3.2. Pfeiffer also provided two useful utilities attached to his model code. One utility, *makestd,* uses the standard atmospheric profile and a user designated surface temperature to create an environmental data file with a standard temperature profile (Pfeiffer, 1994: D-1). Note that this utility does not provide for wind data. The other utility, *getmet*, allows the user to download raw upper air meteorological data from any of numerous sources on the Internet and convert the data into the model-ready environmental data file. The raw data are also available from base or airport weather offices (Pfeiffer, 1994:C-1).

The jettison data file provides all of the specific information on the jettison event, including, aircraft heading, location, airspeed, jettison rate, duration of jettisoning, and initial droplet size. The jettison data file is presented in Figure 3.3. Note that all values can be obtained by members of the aircraft crew at the time of the jettison event with the exception of the initial droplet size and plume width which are predetermined theoretically for each aircraft type. The initial plume width associated with a particular aircraft or jettison configuration is assumed due to the effect of the aircraft wake in spreading the initial plume (Pfeiffer, 1994:3-4).

Finally, the fuel data file is presented in Figure 3.4. The AFIT Model uses Clewell's fuel component models (Clewell, 1981: 5,6). Because this file is modifiable, the model can be used to evaluate various fuel compositions.

```
file:  dayton.atm

DESCRIPTION
-----------


This is a sample environmental data file.
Valid fields and formats are

  thermo_data=altitude;pressure;temperature;

        where altitude is in meters, pressure is in millibars (hPa)
        and temperature is in Celsius

  wind_data=altitude;wind direction;wind speed;

        where altitude is in meters, wind direction is in degrees
        on the compass, and wind speed is in knots

Data must be sorted highest to lowest altitude.

Sample:          thermo_data= 6304.4; 468.0;-14.9;
dayton.atm       thermo_data= 4840.8; 570.0; -6.1;
                 thermo_data= 4123.9; 624.0; 0.0;
                 thermo_data= 1500.0; 850.0; 16.2;
                 thermo_data= 774.0; 925.0; 20.6;
                 thermo_data= 452.7; 947.0; 21.0;
                 thermo_data= 0.0; 978.0; 14.4;
                 wind_data= 6096.0;275.0; 44.0;
                 wind_data= 4876.8;265.0; 40.0;
                 wind_data= 2133.6;300.0; 28.0;
                 wind_data= 1500.0;280.0; 36.0;
                 wind_data= 914.4;265.0; 42.0;
                 wind_data= 609.6;255.0; 44.0;
                 wind_data= 304.8;210.0; 8.0;
                 wind_data= 0.0;210.0; 7.0;
```

Figure 3.2 Sample Environmental Data File and Variable Descriptions (Pfeiffer, 1994: B-4) file: kc135.dat

DESCRIPTION

This is a jettison data file for the model.

Valid fields are:

mean_drop_diameter= (drop diameter in micrometers)
altitude= (release altitude in meters)
airspeed= (airspeed at release in m/s)
duration= (duration of release in seconds)
heading= (aircraft heading at release)
latitude= (aircraft latitude at start of release)
longitude= (aircraft longitude at start of release)
plume_width= (initial plume width in meters)
rate= (jettison rate in kg/s)

All fields are optional. If not specified, a field will be assigned a default value. For latitude and longitude, North and East are positive, and the numbers should be decimal degrees, not degrees and minutes.

Sample: kc135.dat	altitude=1500.0 airspeed=175.0 duration=600.0 heading=180.0 latitude=39.54 longitude=-84.12 mean_drop_diameter=270.0 plume_width=100.0 rate=50.0

Figure 3.3 Sample Jettison Data File and Variable Descriptions (Pfeiffer, 1994: B-3)

```
file:  jp8.dat

DESCRIPTION
-----------
This is a sample fuel data file. Valid fields and formats are

fuel_type=(character string label for the fuel)
number_of_components=(integer number of components)
component=label;volume percent;molecular weight;boiling point;density;

where:  label is a character string (maximum 30 characters)
          describing the component, volume percent.
        volume percent is the volume fraction of the component.
        molecular weight is in kg/kmol
        boiling point is at standard temperature and pressure,
          in Kelvin
        density is in kg/m^3

The 'number_of_components=' MUST appear before any components.

Sample:    fuel_type=JP-8 (Clewell)
jp8.dat    number_of_components=27
           component=C8 paraffins; 0.003;114.2;391.15; 700.0
           component=C8 cycloparaffins; 0.002;112.2;397.15; 780.0
           component=C8 aromatics; 0.001;106.2;412.15; 870.0
           component=C9 paraffins; 0.024;128.3;415.15; 720.0
           component=C9 cycoloparaffins; 0.015;126.2;427.15; 800.0
           component=C9 aromatics; 0.010;120.2;438.15; 880.0
           component=C10 paraffins; 0.056;142.3;433.15; 720.0
           component=C10 cycloparaffins; 0.035;140.3;444.15; 800.0
           component=C10 aromatics; 0.023;134.2;450.15; 860.0
           component=C11 paraffins; 0.087;156.3;469.15; 740.0

                    (truncated to fit in text box)
```

Figure 3.4 Sample Fuel Data File and Variable Descriptions (Pfeiffer, 1994: B-5)

3.2.2 Parameter Evaluation.

The AFIT Model allows an extensive amount of variation in the input data files. The primary variable under consideration in this research was altitude, assuming that releases at higher altitudes would result in greater dispersion and lower concentrations. We were also interested in the effect of the aircraft heading in respect to the direction of the wind. Therefore, we evaluated jettison events at 300 m, 500 m, 1000 m, 3000 m, 6000 m, and 9000 m. Cases at these altitudes were run for aircraft headings from 45 degrees to 360 degrees at 45 degree increments. Results of interest were the maximum concentration of fuel at ground fall and the mass fraction remaining of the fuel mass.

The environmental data files are standard temperature profiles created with the *makestd* utility for surface temperatures of -20 °C, 0 °C, and 20 °C. The cases are evaluated at all three temperatures. The wind data are given as a constant 8 knots and a 270 degree direction. Figure 3.5 presents a sample environmental file for the parameter studies.

Except for the aircraft heading and release altitude, all other values in the jettison data file are held constant. The mean drop diameter is listed as 270 micrometers. This value was calculated by Clewell for the KC-135 and determined to be reasonable and representative (Clewell, 1980(c):60, Pfeiffer, 1994:4-2). The release airspeed is 175 m/s. The release duration is 300 seconds. The jettison rate is 50 kg/s. The initial plume width is 100 meters. A sample jettison data file used for the parameter studies is presented in Figure 3.6.

```
thermo_data=10000.0; 212.92;-85.00;
thermo_data= 9000.0; 254.54;-78.50;
thermo_data= 8000.0; 302.52;-72.00;
thermo_data= 7000.0; 357.57;-65.50;
thermo_data= 6000.0; 420.47;-59.00;
thermo_data= 5000.0; 492.05;-52.50;
thermo_data= 4000.0; 573.18;-46.00;
thermo_data= 3000.0; 664.82;-39.50;
thermo_data= 2000.0; 767.99;-33.00;
thermo_data= 1000.0; 883.75;-26.50;
thermo_data=    0.0;1013.25;-20.00;
wind_data=10000.0;270.0;8.0;
wind_data=0.0;270.0;8.0;
```

(File reduced to fit in text box. Data at 500 meter increments deleted)

Figure 3.5 Sample Environmental Data File for Parameter Studies

```
# Fuel jettison release data
#
mean_drop_diameter=270.0
altitude=9000.0
airspeed=175.0
heading=45.0
latitude=39.54
longitude=-84.12
duration=300.0
rate=50.0
plume_width=100.0
```

Figure 3.6 Sample Jettison Data File for Parameter Studies

Another variable of interest was the wind speed. We varied the wind speed from 3 knots to 8 knots for jettison releases at 300 m, 1500 m, and 6000 m. The wind direction is 270 degrees and the aircraft heading is 180 degrees, creating a crosswind release. The surface temperature is 20 °C. Except for the different altitudes, all other variables in the jettison data file are the same as specified for the previous study (Figure 3.6).

3.2.3 Wind Direction Variation Requirement.

The results of the wind speed parameter study (Table 4-3 and Table 4-4) show that as wind velocity increased, the concentration at the surface also increased. We expected the concentration to decrease with increasing velocity because of increasing dispersion. Equation 2.23 and Equation 2.24 show that the eddy diffusion coefficients are functions of the wind velocity and wind shear, the changing of wind direction. The environmental file used for these cases was a standard temperature profile with a constant wind profile. Therefore, our cases were calculated with zero wind shear. The AFIT Model uses the wind shear to estimate the standard deviation of the horizontal wind direction. We will show that for the range of wind speeds used in our case studies, that assuming a standard deviation of the horizontal wind direction, σ_θ, of zero will result in decreased dispersion as the wind speed variable is increased.

Using Equation 2.23 and Equation 2.25, and assuming that all other variables are constant, we define the function *f(u)* by:

$$f(u) = u(\sigma_\theta + \sigma_\theta^{\prime})^2 \tag{3.1}$$

where

$$\sigma_\theta^{\prime} = \pi \cdot e^{-0.367u} \tag{3.2}$$

and by substitution, we have

$$f(u) = u(\sigma_\theta + \pi \cdot e^{-0.367u})^2 \tag{3.3}$$

Expanding the function, we have

$$f(u) = u \cdot \sigma_\theta^2 + 2 \cdot u \cdot \pi \cdot \sigma_\theta \cdot e^{-0.367u} + u \cdot \pi^2 \cdot e^{-0.734u} \tag{3.4}$$

If we take the derivative of the function with respect to u, we can analyze the function's response to u. If the derivative is positive for a given range of u, then the dispersion will increase as a function of the increasing u. Differentiating Equation 3.4 yields

$$\begin{aligned} f^{\prime}(u) = {} & \sigma_\theta^2 + 2 \cdot \pi \cdot \sigma_\theta \cdot e^{-0.367u} - 0.734 \cdot u \cdot \pi \cdot \sigma_\theta \cdot e^{-0.367u} \\ & + \pi^2 \cdot e^{-0.734u} - 0.734 \cdot u \cdot \pi^2 \cdot e^{-0.734u} \end{aligned} \tag{3.5}$$

If σ_θ equals zero then we can simplify Equation 3.5 to

$$f^{\prime}(u) = \pi^2 \cdot e^{-0.734u} - 0.734 \cdot u \cdot \pi^2 \cdot e^{-0.734u} \tag{3.6}$$

Equation 3.6 can be further simplified to

$$f'(u) = \pi^2 \cdot e^{-0.734u}(1 - 0.734 \cdot u) \tag{3.7}$$

From Equation 3.7, we see that if $1 - 0.734\,u < 0$, then $f'(u)$ is negative and dispersion decreases as u increases. From this relation, we calculate that 1.36 m/s is the maximum u allowed to generate increased dispersion when σ_θ is equal to zero. Figure 3.7 demonstrates this relation and that as u exceeds 10 m/s, $f'(u)$ approaches zero but does not become positive.

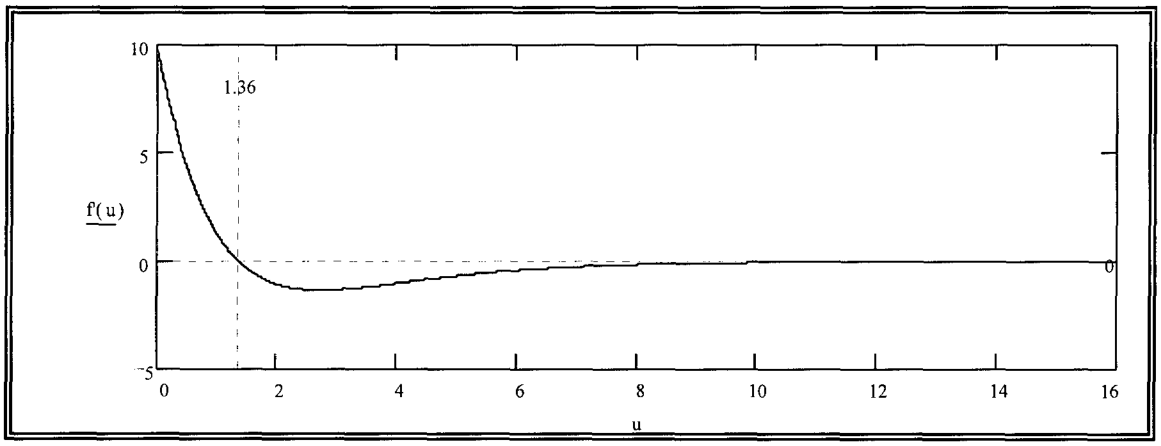

Figure 3.7 Relationship Between Equation 3.6 and Wind Velocity for $\sigma_\theta = 0$.

Therefore, for σ_θ equal to zero, our range of wind velocities from 1.5 m/s to 4.1 m/s has the result of decreasing dispersion as the velocity increases. Figure 3.8 shows that for Equation 3.4, dispersion increases from 0 m/s to 1.36 m/s and then decreases to zero as the wind velocity increases.

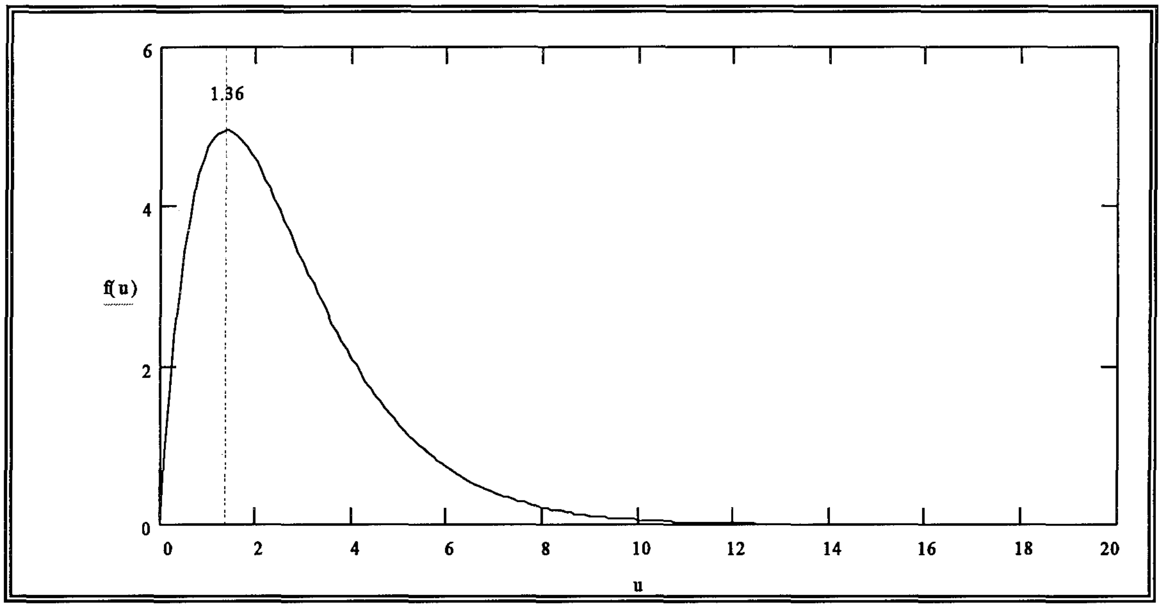

Figure 3.8 Relationship Between Equation 3.4 and Wind Velocity for $\sigma_\theta = 0$.

Wind shear must be included to calculate a value for σ_θ and ensure that dispersion increases as a function of increasing wind velocity. By using real upper air data, this criteria is met. The sample environmental data file for Dayton, Ohio in Figure 3.2 demonstrates wind direction variation and also that the wind velocity can be very great at higher altitudes.

We now need to identify the rate of change in the wind direction which will result in a σ_θ value which will generate positive eddy diffusion coefficients for the AFIT Model. Using Equation 3.5, we can incrementally increase σ_θ until the function is positive for all values of u considered. Figure 3.9 demonstrates that by letting σ_θ be 1.402 our function will be positive for our range of wind speeds. Figure 3.10 shows that Equation 3.4 continues to increase as u increases for σ_θ = 1.402. Therefore, the eddy diffusion coefficients will increase as wind velocity increases if σ_θ is equal to or greater than 1.402.

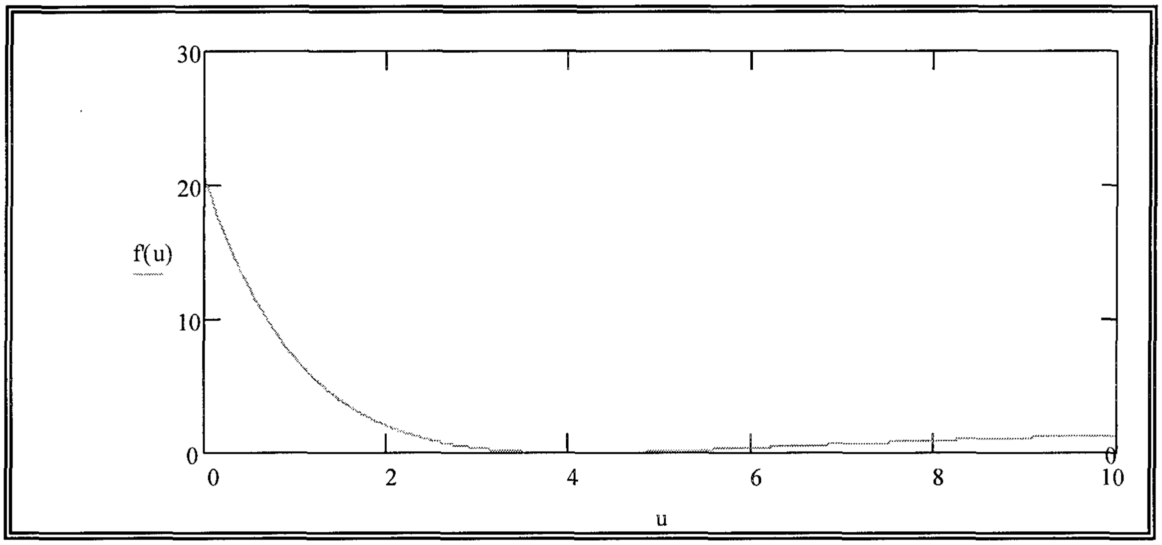

Figure 3.9 Relationship Between Equation 3.5 and Wind Speed when σ_θ is 1.402

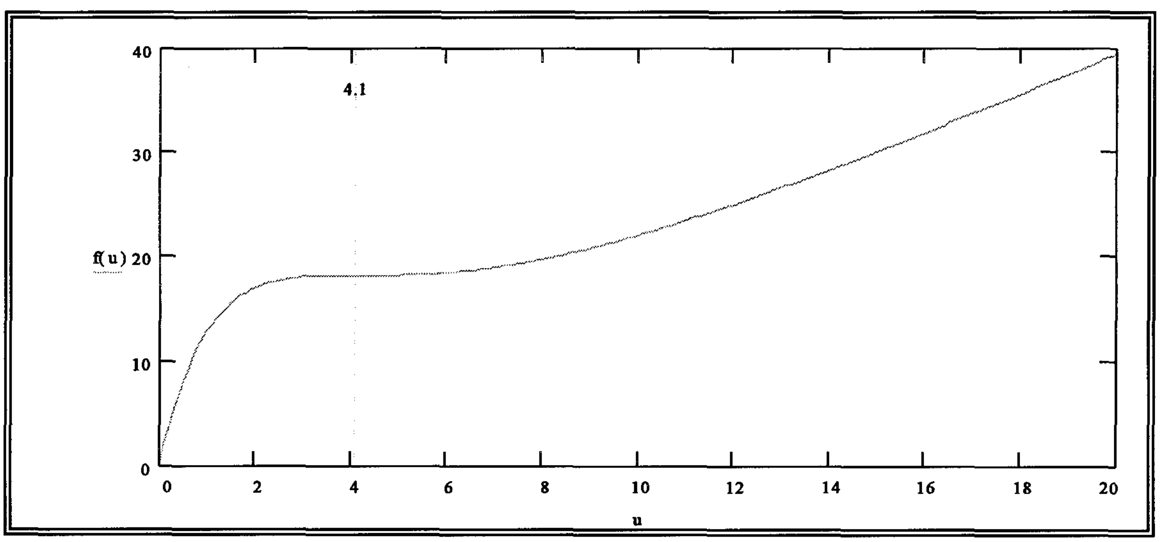

Figure 3.10 Relationship Between Equation 3.4 and Wind Speed when σ_θ is 1.402.

This critical value of σ_θ is associated with wind speeds near 4.1 m/s. The AFIT model calculates σ_θ by taking the difference between the wind direction 100 meters above the altitude of the plume and 100 meters below the altitude of the plume. This difference is then converted from degrees to radians. A σ_θ value of 1.402 (radians) therefore corresponds to 80.33 degrees. This results in a wind direction variation requirement of 80.33 degrees per 200 meters or 0.402 degrees per meter. To evaluate the effect of wind shear, we have created an environmental data file which changes wind direction 90° every 200 meters.

Note that a wind directional difference of 90° every 200 meters is very improbable. We are artificially creating this environmental data file to generate our desired results. Additional research must be accomplished to determine a better method to calculate σ_θ from the available data. We also note that the model calculates dispersion for the entire height of the jettison release. Dispersion should be calculated primarily within the planetary boundary layer. The model can be modified to calculate the altitude of the boundary layer and begin applying the dispersion model at that altitude.

3.3 Comparison to Fuel-Dumping Impact Assessment Model (FDIAM)

As discussed in the background section, the Fuel-Dumping Impact Assessment Model (FDIAM) is an independent effort to model the impact of jettisoned fuel on the ground surface (Ferrenberg, 1993). The objective of comparing the AFIT Model to FDIAM is to determine the effect of the different assumptions made by the models. Specifically, FDIAM incorporates an algorithm to calculate the initial temperature of the fuel based on the duration of the aircraft flight prior to the jettison event. FDIAM also adds algorithms which relaxed the assumption that the droplets are constantly at a fixed velocity (Ferrenberg, 1993:13). Finally, FDIAM does not incorporate a dispersion model as does the AFIT model. Instead, FDIAM tracks the movement of individual packets of droplets, and upon ground impact, determines the dispersion of similar packets (Ferrenberg, 1993:7).

The Armstrong Laboratory report on FDIAM presents the results of four cases. Using the AFIT Model, we emulated the input data for two of those cases, one each for JP-4 and JP-8, to compare the output of the two models. The other two FDIAM cases were for sunlight and the absence of sunlight. The AFIT Model does not intuitively differentiate between sunlight and no sunlight. Figure 3.7 lists the input data for Case 1 (JP-4). The input data for Case 2 was identical except for the substitution of JP-8 for JP-4. We emulated the FDIAM input data within the AFIT Model's input files. FDIAM uses the air temperature at the release altitude and the ground temperature to calculate a linear temperature lapse rate. We used this FDIAM temperature lapse rate to calculate our temperature profile in the AFIT Model environmental data file. The FDIAM input data does not include the atmospheric pressure profile. Because the AFIT Model environmental data file requires the atmospheric pressure at each listed altitude, we used the standard pressure at the altitudes specified by the FDIAM input data file. All other values for the wind data were copied directly into the AFIT Model environmental data file. The AFIT Model environmental data file used to compare the AFIT Model to FDIAM is presented in Figure 3.12. (Note: FDIAM references Sea

Level as 0.0 altitude, while the AFIT Model simply refers to the surface as 0.0 altitude. Therefore, 1000 feet must be subtracted from each FDIAM wind data point and converted to meters.)

FUEL DUMPING IMPACTS ASSESSMENT MODEL

CASE RUN ON 01-12-1993
TIME = 15:45:47

INPUT DATA

AIRCRAFT IS KC-135 USING JP-4
FUEL DUMP RATE IS 2000 POUNDS PER MINUTE
AIR TEMPERATURE AT DUMP ALTITUDE IS -8 (deg. C)
GROUND TEMPERATURE IS 20 (deg. C)
SUN WAS NOT SHINING ON DUMPED FUEL CLOUD
PRIOR TO DUMP, AIRCRAFT FLEW FOR APPROX. 3 HOURS AT APPROX. 25000 FEET
AT APPROXIMATELY MACH .3

WIND DATA

ALTITUDE (feet)	DIRECTION (HEADING)	VELOCITY (Knots)
1000 (ground)	80	5
5000	135	5
10000	90	15
15000	90	20
18000	130	0
20000	120	50

FLIGHT SEGMENTS INPUT

SEGMENT	HEADING (Degrees)	ALTITUDE (Kfeet)	GRND. SPEED (knots)	DURATION (minutes)
1	135.00	20.00	500.00	5.00
2	225.00	10.00	600.00	6.00
3	335.00	15.00	400.00	2.00
4	0.00	2.00	500.00	2.00

TOTAL QUANTITY OF FUEL DUMPED = 30000 (pounds)

Figure 3.11 Case 1 (JP-4) FDIAM Input Data (Ferrenberg, 1993:31)

```
thermo_data= 7315.2; 375.0;-15.368;
thermo_data= 5791.2; 466.0;-8.00;
thermo_data= 5181.6; 505.0;-5.053;
thermo_data= 4267.2; 570.0; -0.632;
thermo_data= 2743.2; 695.0; 6.737;
thermo_data= 1219.2; 845.0; 14.105;
thermo_data= 0.0; 980.0; 20.00;
wind_data=7315.2;120.0;50.0;
wind_data=5791.2;120.0;50.0;
wind_data=5181.6;130.0; 0.0;
wind_data=4267.2;90.0;20.0;
wind_data=2743.2;90.0;15.0;
wind_data=1219.2;135.0;5.0;
wind_data=0.0;120.0;5.0;
```

Figure 3.12 AFIT Model-FDIAM Case 1 Environmental Data File

We created jettison data files for the AFIT Model which emulated the FDIAM input data. Because the AFIT Model allows only one segment at a time, we separated the FDIAM cases into the four flight segments and created four initialization and jettison data files each for JP-4 and JP-8. Figure 3.9 presents the jettison data file for the first flight segment for Case 1. Figure 3.10 presents the initialization file for the first flight segment for Case 1.

The heading, altitude (in meters), jettison rate (in kg/s), and duration were entered directly into the jettison data file. The airspeed was assumed to be the same as the ground speed given in Figure 3.7 and was converted to meters per second. FDIAM does not provide values for the mean drop diameter and plume width. The values used are those determined by previous research and assumptions (Clewell, 1980(c):60). FDIAM also does not provide a map-relative location. Therefore, the latitude and longitude values are not relevant in this comparison.

```
#
# Fuel jettison release data
#
mean_drop_diameter=270.0
altitude=5791.2
airspeed=257.2
heading=135.0
latitude=39.54
longitude=-84.12
duration=300.0
rate=15.12
plume_width=100.0
```

Figure 3.13 AFIT Model-FDIAM Case 1 Jettison Data File

```
environmental_data=case1.atm
jettison_data=case1-1.dat
fuel_data=jp4.dat
output_messages=case1-1.msg
output_map=case1-1.map
output_grid=case1-1.grd
```

Figure 3.14 AFIT Model-FDIAM Case 1 Initialization File

3.4 Analysis of Evaporation after Ground Fall

To evaluate the significance of JP-8 contamination at ground fall, we decided to determine the effect of surface evaporation. If surface evaporation occurs in a reasonable time period, then the concentration of JP-8 reaching the surface may be considered insignificant. As a result of the need to model surface evaporation after groundfall, a modified version of the AFIT Model was developed (Pfeiffer, 1995). The simplifying assumptions are as follows.

The first assumption is that the geometry of the fuel droplet changes from a sphere to a disk at ground fall. A disk geometry is used to simplify the mathematics of calculating the volume and surface area of a more realistic ellipsoid, spherical cap, or diffusive film. The droplet disk will have the same volume as the droplet sphere immediately before ground fall. Another consideration is that the droplet may break up and scatter on impact. To account for this possibility, we kept the droplet disk thickness-to-radius ratio low, using 0.05 for our calculations. The thickness-to-radius ratio is such that:

$$w = disc\_ratio \cdot r \tag{3.8}$$

where

w = disk thickness

r = disk radius

$disc\_ratio$ = thickness-to-radius ratio

Therefore, the volume of the disk is:

$$V = \pi \cdot r^2 \cdot w$$
$$= \pi \cdot r^2 \cdot disc\_ratio \cdot r \tag{3.9}$$
$$= \pi \cdot r^3 \cdot disc\_ratio$$

Substituting Equation 3.9 into Equation 2.9 and solving for *r* yields:

$$r = \sqrt[3]{\sum_{i=1}^{n} \frac{m_i}{\rho_i} \frac{1}{\pi \cdot disc\_ratio}} \tag{3.10}$$

The surface area of interest for evaporation calculations is only that area exposed to the atmosphere. To simplify the calculations, the top surface area of the disk and the sides combine to give us the evaporative surface area, S_E:

$$S_E = (\pi \cdot r^2) + (2 \cdot \pi \cdot r \cdot w)$$
$$= (\pi \cdot r^2) + (\pi \cdot r^2 \cdot 2 \cdot disc\_ratio) \tag{3.11}$$
$$= (\pi \cdot r^2) \cdot (1 + 2 \cdot disc\_ratio)$$

This surface evaporation subroutine has been added to the AFIT Model (Pfeiffer, 1995). The thickness-to-radius ratio, *disc_ratio*, has been added to the jettison data file, *case.dat*. The droplet structure has been modified to have a surface area attribute. The surface area is calculated based on the geometry of the droplet at the time of the calculation. When calculating evaporation of the droplet sphere, the heat and mass transfer coefficients are determined by using the droplet diameter as the critical length. When the droplet becomes a disk, the thickness, w, is used as the critical length (Holman, 1976:359). At ground fall, all advection and dispersion calculations are terminated. Evaporation calculations continue until all of the mass of the fuel is evaporated. The results are recorded in the *case.msg* file. This subroutine was added to the model and run for all of the cases listed in the parameter study.

This concludes our prsentation of the approach used in this thesis effort. The next chapter will present the results generated by this approach.

IV. Discussion of Results

4.1 Introduction

This chapter presents results from our parameter studies described in Chapter 3 using the AFIT Model and comparisons of results from the AFIT Model with results from the Fuel-Dumping Impact Assessment Model. The results provide insight into the significance of jettisoned JP-8 jet fuel compared to JP-4 jet fuel. The chapter will conclude with a presentation of the results of our surface evaporation study.

4.2 AFIT Model Parametric Studies

Our parameter studies compared the surface impact of JP-4 and JP-8 jettisoned under identical conditions. Pfeiffer was able to validate the results of the AFIT Model for JP-4 releases by comparing his evaporation results with those of Clewell and dispersion results with an exact line source solution (Pfeiffer, 1994:4-1, 4-33). Therefore, we will assume to validity of the AFIT Model for our cases. The objective of the parameter studies was to evaluate the influence of specific variables and compare the difference in results between JP-4 and JP-8.

Table 4.1 and Table 4.2 present the concentrations calculated by the AFIT Model for various release altitudes and aircraft orientations for JP-4 and JP-8, respectively. The parameter studies were generated using the environmental data file presented in Figure 3.5 and the jettison data file presented in Figure 3.6 with altitude and aircraft orientation the only variables. A surface temperature of -20°C is presented as the worst case condition.

Table 4.1 Maximum JP-4 Ground Deposition Concentration (10^{-6} kg/m^2) at -20°C

Aircraft Heading vs. Altitude Above Ground Surface at -20°C						
	300 m	500 m	1000 m	3000 m	6000 m	9000 m
45°	80.29	48.34	24.05	8.596	6.169	5.588
90°	80.27	48.32	24.04	8.594	6.168	5.588
135°	80.29	48.34	24.05	8.596	6.169	5.588
180°	76.22	45.87	22.81	8.151	5.850	5.297
225°	80.29	48.34	24.05	8.596	6.169	5.588
270°	80.27	48.32	24.04	8.594	6.168	5.588
315°	80.29	48.34	24.05	8.596	6.169	5.588
360°	76.22	45.87	22.81	8.151	5.850	5.297

Table 4.2 Maximum JP-8 Ground Deposition Concentration (10^{-6} kg/m^2) at -20°C

Aircraft Heading vs. Altitude Above Ground Surface at -20°C						
	300 m	500 m	1000 m	3000 m	6000 m	9000 m
45°	386.7	289.8	193.6	106.2	77.65	66.32
90°	386.6	289.7	193.5	106.1	77.64	66.32
135°	386.7	289.8	193.6	106.2	77.65	66.32
180°	367.3	275.1	183.7	100.7	73.64	62.90
225°	386.7	289.8	193.6	106.2	77.65	66.32
270°	386.6	289.7	193.5	106.1	77.64	66.32
315°	386.7	289.8	193.6	106.2	77.65	66.32
360°	367.3	275.1	183.7	100.7	73.64	62.90

As the release altitude increases, the fuel concentration at ground fall decreases as expected. The aircraft orientation did not significantly influence the resulting surface concentration. The concentrations were relatively equal for all orientations evaluated except for the cases in which the aircraft orientation during the jettison was 90° (and 270°) from the direction of the wind. In these two cases, the aircraft orientation created a crosswind release which increased dispersion in the *y* direction. We can conclude from these results that a crosswind release will result in the greatest dispersion and therefore reduce the concentration levels. All other release orientations will result in greater fuel concentrations. Therefore,fuel jettisoning should be accomplished at a 90° angle to the prevalent wind direction.

Comparing the results of Table 4.1 to Table 4.2, we note that JP-8 releases result in greater concentrations at ground fall than JP-4 releases under the same conditions. The results of both are presented at the same scale of 10^{-6} kg/m^2 for effective comparison. These results clearly demonstrate the effect of the lower volatility composition of JP-8 jet fuel. Figure 4.1 graphically demonstrates the difference in concentration levels at the surface for JP-4 and JP-8.

The AFIT Model *case.msg* file provides the maximum concentrations calculated by the dispersion model and also the mass fraction remaining, which is the present amount of fuel divided by the total amount of fuel jettisoned. Table 4.3 and Table 4.4 present the mass fraction remaining at the surface for JP-4 and JP-8, respectively. Results are presented for cases at -20°C, 0°C, and 20°C and release altitudes from 300 meters to 9000 meters. Table 4.4 has been expanded to include data from calculations at 10°C.

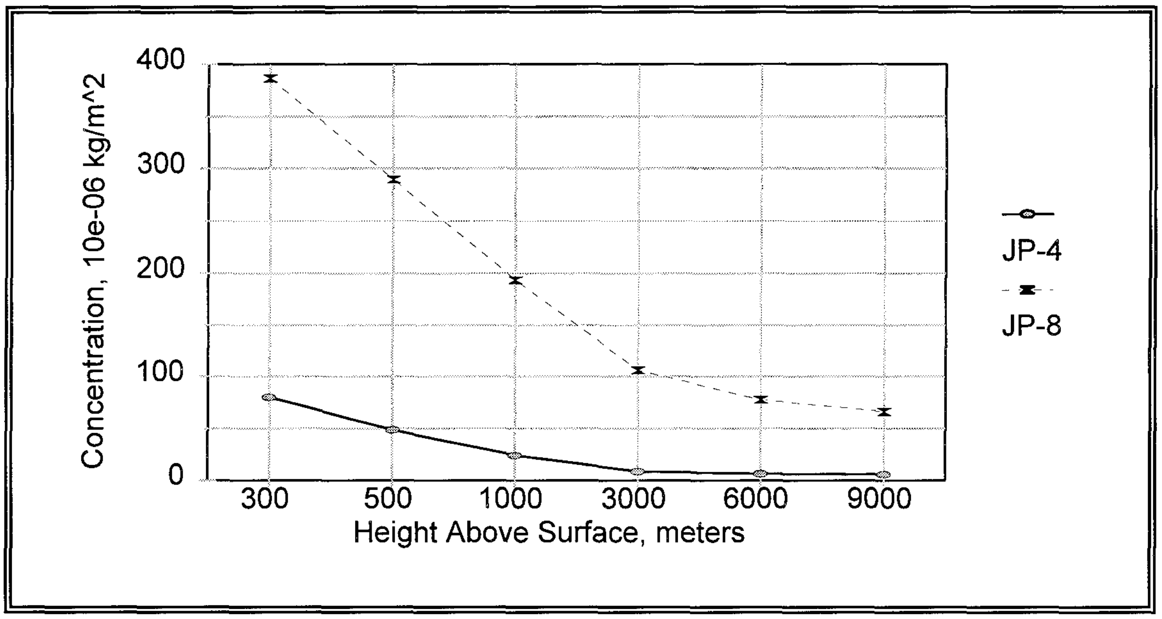

Figure 4.1 Maximum Concentrations vs. Release Altitudes at -20°C.

Table 4.3 JP-4 Mass Fraction Remaining at Ground fall, Release Altitudes vs. Temperatures

	-20°C	0°C	20°C
300 m	0.22841	0.03510	0.00164
500 m	0.18281	0.02666	0.00156
1000 m	0.13415	0.02079	0.00141
1500 m	0.11010	0.01799	0.00131
3000 m	0.08376	0.01455	0.00118
6000 m	0.07796	0.01362	0.00116
7500 m	0.07847	0.01371	0.00116
9000 m	0.07924	0.01385	0.00117

Table 4.4 JP-8 Mass Fraction Remaining at Ground fall, Release Altitudes vs. Temperatures

	-20°C	0°C	10°C	20°C
300 m	0.88028	0.62706	0.39232	0.15705
500 m	0.84305	0.53218	0.26932	0.10008
1000 m	0.79131	0.39453	0.15070	0.05812
1500 m	0.76514	0.32366	0.11952	0.03571
3000 m	0.73564	0.24682	0.09584	0.00422
6000 m	0.72852	0.22768	0.08955	0.00150
7500 m	0.72924	0.22849	0.08976	0.00150
9000 m	0.73027	0.23027	0.09022	0.00151

From these results, we can see that more of the lower volatile JP-8 jet fuel remains when the fuel plume reaches the surface. The mass fraction remaining of JP-4 is essentially negligible except for releases less than 1500 meters at temperatures well below 0°C. For JP-8, the surface temperature is much more significant as a considerable fraction of the original mass remains for cases calculated for a surface temperature of 0°C and even for 10°C at low altitude releases. For both JP-4 and JP-8, the mass fraction remaining at ground fall is unchanged as elevations exceed 6000 meters. The temperatures at 6000 meters for all temperature profiles is well below 0°C and therefore do not contribute significantly to droplet evaporation. If we concentrate on values for release altitudes at or greater than 6000 meters, we can conclude that temperatures around 0°C and below are critical for JP-8 jet fuel. Figure 4.2 graphically presents these results.

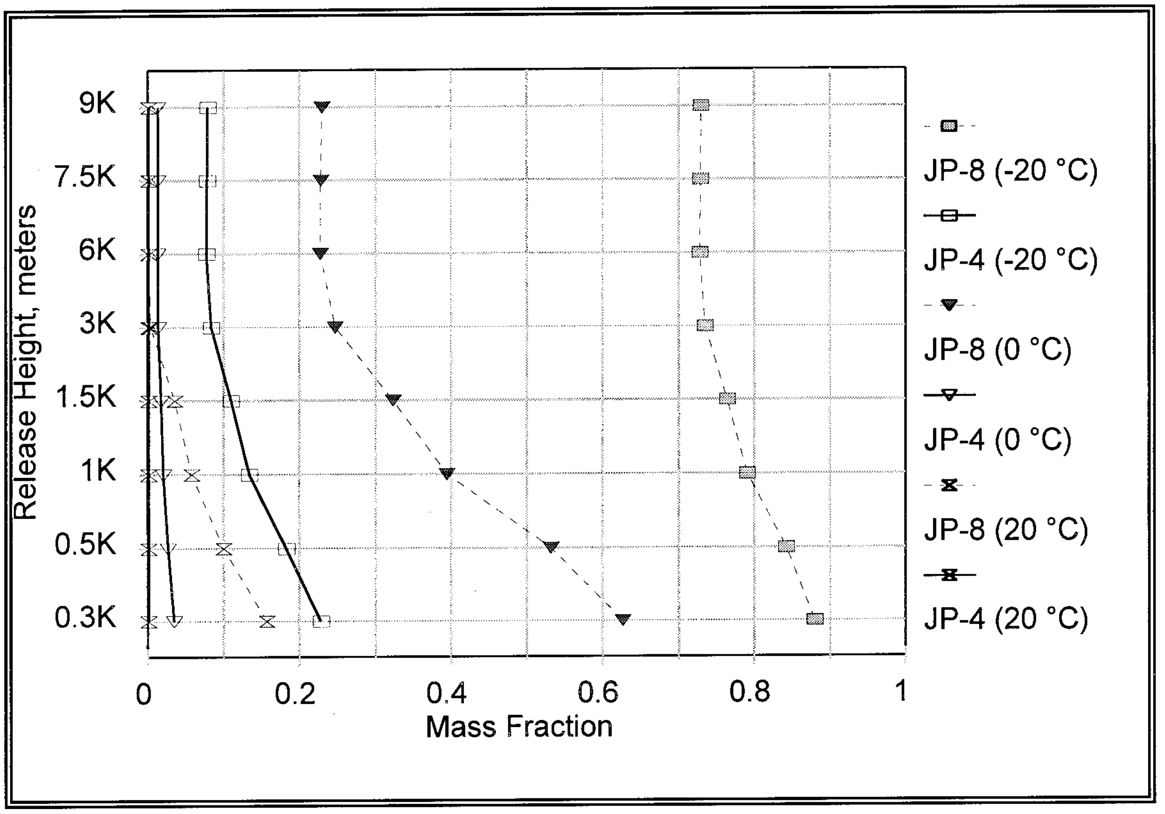

Figure 4.2 Mass Fraction of Jet Fuel Remaining at Ground Fall vs. Release Altitude

We also studied the effect of wind speed to the maximum concentration of jet fuel at the surface. Table 4.5 and Table 4.6 present the maximum ground fall concentrations for jettison release altitudes of 300 meters, 1500 meters, and 6000 meters and wind velocities of 3 knots to 8 knots. The maximum concentration at ground fall of jet fuel released at 6000 meters over the range of wind velocities is presented in Figure 4.3. Note that these results are generated by using an environmental data file with a constant wind profile. Therefore, there is no wind shear.

Table 4.5 Maximum JP-4 Ground Deposition Concentrations for Various Wind Speeds and No Wind Shear (10^{-9} kg/m^2)

Wind Speed vs. Altitude Above Ground Surface at 20°C			
	300 m	1500 m	6000 m
3.0 knots	48.99	12.78	6.771
4.0 knots	61.23	15.97	8.463
5.0 knots	78.71	20.62	10.93
6.0 knots	104.1	27.17	14.40
7.0 knots	139.0	36.31	19.24
8.0 knots	187.6	49.01	25.97

Table 4.6 Maximum JP-8 Ground Deposition Concentrations for Various Wind Speeds and No Wind Shear (10^{-9} kg/m^2)

Wind Speed vs. Altitude Above Ground Surface at 20°C			
	300 m	1500 m	6000 m
3.0 knots	13670	1086	21.37
4.0 knots	17070	1357	26.72
5.0 knots	21990	1751	34.49
6.0 knots	28880	2307	45.44
7.0 knots	38390	3081	60.72
8.0 knots	51510	4156	81.96

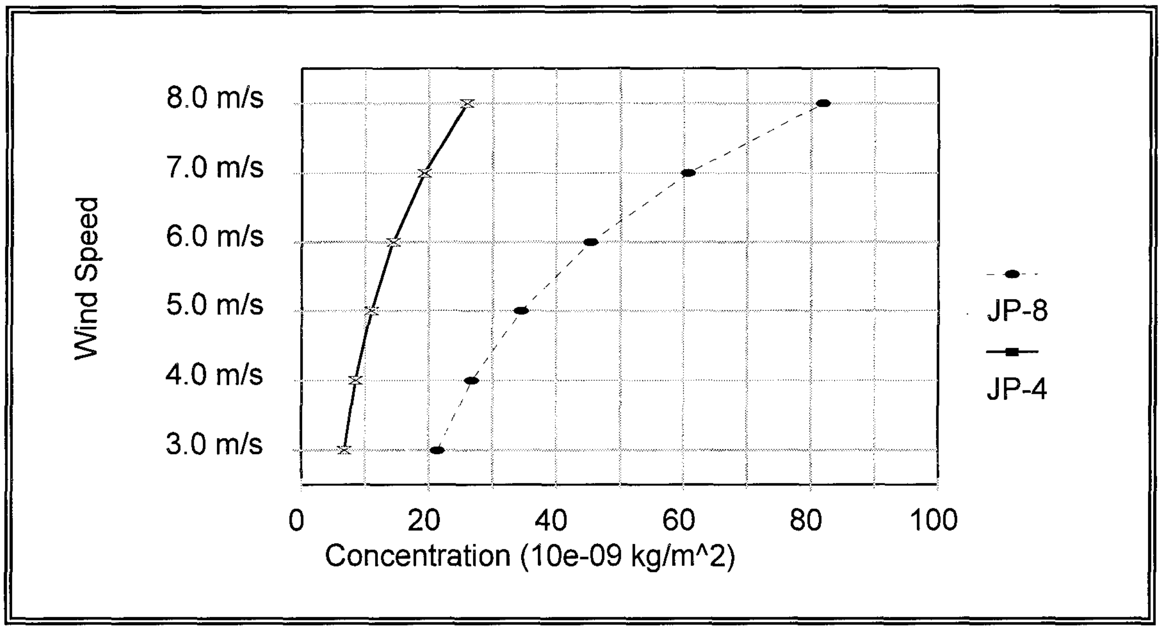

Figure 4.3 Maximum Concentrations vs. Wind Speed at 20°C from a 6000 m Release (No Wind Shear).

Table 4.7 compares the results of using an environmental data file with wind shear to the results using environmental data file without wind shear. Our environmental data file with wind shear was prepared to ensure that σ_θ was equal to or greater than 1.402. The concentration of jet fuel at the surface decreases significantly when wind shear is included in the environmental data file. Likewise, the results of using wind shear show ground fall concentrations decreasing as a function of increasing wind velocity as expected. The groundfall impact of jettisoned JP-8 jet fuel is approximately 7 times greater than the impact of JP-4 jet fuel under the same release conditions. Figure 4.4 graphically presents the results using a wind shear of equal to or greater than 1.402.

Table 4.7 Maximum Concentrations With Respect to Wind Speed and Wind Shear (10^{-10} kg/m^2)

JP-4 and JP-8 Releases at 6000 m and at 20°C Surface Temperature				
	JP-4 ($\sigma_\theta = 0$)	JP-4 ($\sigma_\theta \geq 1.402$)	JP-8 ($\sigma_\theta = 0$)	JP-8 ($\sigma_\theta \geq 1.402$)
3.0 knots	67.7	11.4	214	78.2
4.0 knots	84.6	10.5	267	73.8
5.0 knots	109	9.79	345	70.2
6.0 knots	144	9.12	454	66.6
7.0 knots	192	8.48	607	62.9
8.0 knots	260	7.86	820	59.2

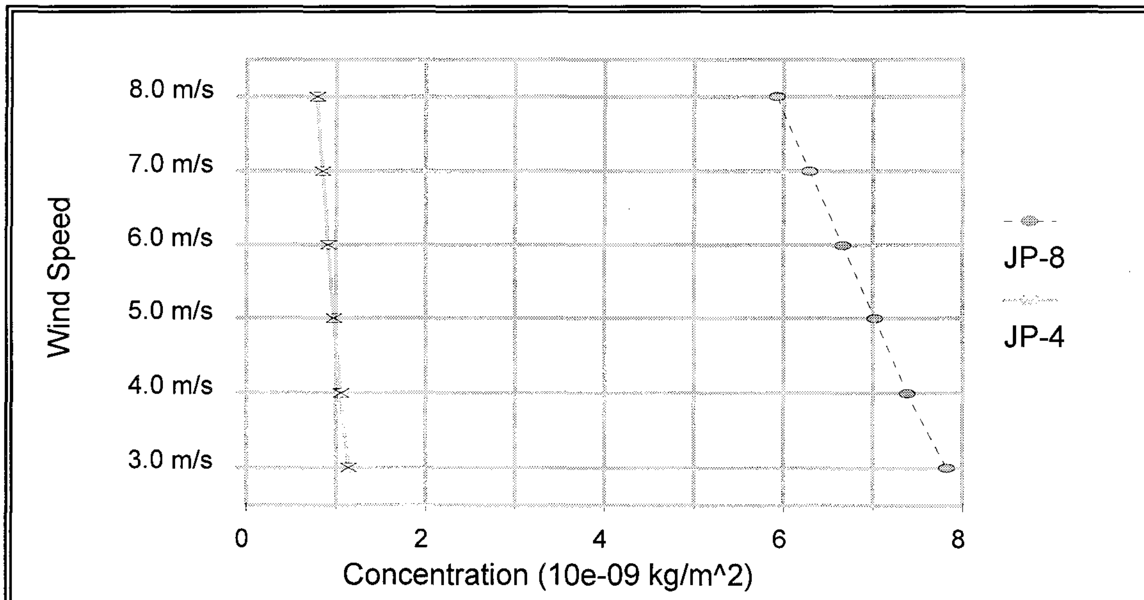

Figure 4.4 Maximum Concentrations vs. Wind Speed at 20°C from a 6000 m Release ($\sigma_\theta \geq 1.402$)

For a release altitude of 6000 meters and wind velocity of 8 knots, the inclusion of wind shear decreased the ground fall concentrations by more than a factor of 13. We can also infer from the results of using an environmental data file with wind shear in Table 4.7 that the results in Table 4.1 and Table 4.2, which were generated by an environmental data file with a wind velocity of 8 knots (4.1 m/s) and without wind shear are overly conservative by at least a factor of 10.

4.3 Comparison to Fuel-Dumping Impact Assessment Model (FDIAM)

We constructed input data files for the AFIT Model to duplicate the jettison event modeled by the Fuel-Dumping Impact Assessment Model (FDIAM). We did not independently run FDIAM but used the results published in the Armstrong Laboratory report (Ferrenberg, 1993). The results of FDIAM for the JP-4 case is presented in Figure 4.5. The ground contamination plot is not reproduced in this thesis report. The plot showed the aircraft dumping flight profile and circles representing contamination. The size of the circles are relative to the concentration of fuel at that location (Ferrenberg, 1993:33).

The total mass remaining at ground fall for JP-4 is 38.10 pounds which converts to 17.28 kg. The total quantity of fuel dumped was 30,000 pounds resulting in 0.00127 mass fraction remaining. This value agrees with our AFIT Model results for cases with a surface temperature of 20°C (Table 4.3).

```
------------------ GROUND GRID SIZE AND LOCATION -----------------------

20 BY 20 GRID
GRID SIZE
        EAST SIDE IS AT 153883.1 METERS
        WEST SIDE IS AT -39059.18 METERS
        NORTH SIDE IS AT 4175.135 METERS
        SOUTH SIDE IS AT -167005.4 METERS
(These dimensions are relative to the aircraft's initial fuel release location)

TOTAL MASS IMPACTING THE GROUND WITHIN THE GRID AREA:
3.810D+01 POUNDS

TIME = 16:00:57

PLOT DATA INFORMATION
        Largest circle represents n ground contamination mass of
        3.95955 kilograms in an area of 8.256992E+07 sq. meters
        Contamination concentration is proportional to plotted circle area
```

Figure 4.5 FDIAM Case 1 (JP-4) Output Data (Without Concentration Plot)

Figure 4.6 presents the FDIAM results of the JP-8 case. The total mass remaining at ground fall of JP-8 is 1,279 pounds or 580.14 kg. Using the total quantity dumped of 30,000 pounds results in a mass fraction remaining of 0.0426. This calculation is also in agreement with the AFIT Model for a surface temperature of 20°C and the altitudes used by FDIAM (Table 4.4).

--------------------- GROUND GRID SIZE AND LOCATION ----------------------

20 BY 20 GRID
GRID SIZE
EAST SIDE IS AT 146856 METERS
WEST SIDE IS AT -38887.89 METERS
NORTH SIDE IS AT 3645.813 METERS
SOUTH SIDE IS AT -145832 5 METERS
(These dimensions are relative to the aircraft's initial fuel release location)

TOTAL MASS IMPACTING THE GROUND WITHIN THE GRID AREA:
1.279D+03 POUNDS

TIME = 16:32:14

PLOT DATA INFORMATION
Largest circle represents a ground contamination mass of
86.97752 kilograms in an area of 6.94117E+07 sq. meters.
Contamination concentration is proportional to plotted circle area.

Figure 4.6 FDIAM Case 2 (JP-8) Output Data (Without Concentration Plot)

Table 4.8 and Table 4.9 compare the total mass impacting the ground calculated by FDIAM with the amount calculated by the AFIT Model. To calculate the results of the AFIT Model we separated the flight profile of Case 1 and Case 2 into four segments. We ran the AFIT Model for each segment and calculated the total mass impacting the surface by multiplying the original quantity of each segment by the mass fraction at ground fall. We then added the results of the four segments to compare with the FDIAM results. For both JP-4 and JP-8, the AFIT Model results were less than calculated by FDIAM. However, the results were of the same magnitude.

Table 4.8 Case 1 (JP-4) Total Mass Impacting Ground Within Grid Area

	AFIT Model	FDIAM
Flight Segment 1	3.81 kg	
Flight Segment 2	5.28 kg	
Flight Segment 3	1.62 kg	
Flight Segment 4	2.96 kg	
Total	13.67 kg	17.28 kg

Table 4.9 Case 2 (JP-8) Total Mass Impacting Ground Within Grid Area

	AFIT Model	FDIAM
Flight Segment 1	5.49 kg	
Flight Segment 2	7.62 kg	
Flight Segment 3	2.32 kg	
Flight Segment 4	258.21 kg	
Total	273.64 kg	580.15 kg

The reason the models give differing results is that the evaporation models are implemented differently. FDIAM incorporated a different vaporization model to counter Clewell's assumption that the droplets experienced infinitely fast internal mixing. However, Ferrenberg noticed that FDIAM underestimated the evaporation rate for longer time periods. His calibration with the AEDC experimental data (Dawbarn, 1975) showed that FDIAM overestimated the evaporation in the early stage which depleted the droplet of the more volatile components. This caused FDIAM's later evaporation rates to be reduced. To counter this effect, Ferrenberg introduced a simple evaporation rate retarder in the early stage which allowed only a certain thickness of the droplet evaporate at a given time. He calibrated the evaporation rate retarder by comparing his results to Dawbarn's JP-4 results (Ferrenberg, 1993:23). Therefore, the rate retarder is optimized for JP-4 and not for JP-8. We conclude that the JP-4 results in Table 4.8 are in satisfactory agreement. However, FDIAM is underestimating the evaporation rate of JP-8, resulting in a much higher mass remaining at ground fall as demonstrated by Table 4.9.

The maximum concentrations for Case 1 and Case 2 are presented in Table 4.10. The results of FDIAM are of the same magnitude as those of the AFIT Model. However, while the AFIT Model generated a lower maximum concentration for JP-4 jet fuel, it generated a higher concentration for JP-8 jet fuel. Note that the maximum concentration reported for the AFIT Model are from the last flight segment which was at the lowest altitude for the FDIAM cases. We suggest that the methods of dispersion calculation account for these differences. While the AFIT Model uses a classical dispersion calculation, FDIAM employs a routine which tracks a single packet of fuel and assigns the fate of other packets accordingly. Because JP-8 jet fuel evaporates at a slower rate than JP-4 jet fuel, the advection and dispersion routines of the models may intrinsically give different results. A closer study of the different dispersion routines used by the models is required to address this discrepancy.

Table 4.10 Comparison of Maximum Concentrations

	AFIT Model	FDIAM
Case 1 (JP-4)	1.50e-08 kg/m^2	4.80e-08 kg/m^2
Case 2 (JP-8)	3.98e-06 kg/m^2	1.25e-06 kg/m^2

4.4 Analysis of Evaporation After Ground Fall

The results of our surface evaporation studies are presented in Table 4.11 through Table 4.18. The results for JP-4 in Table 4.3 show that the mass fraction of JP-4 was essentially negligible for all cases. Therefore, we concentrated on the evaporation of JP-8 for the surface evaporation studies.

The following tables present the time required for complete evaporation of the total mass remaining of JP-8 for surface temperatures of -20°C, 0°C, and -20°C for altitudes from 300 m to 9000 m. The tables also provide the mass fraction of fuel remaining at ground fall before surface evaporation begins. The Start Time is the time at which the plume reaches the surface. The End Time is when all of the fuel has been evaporated.

The end time is adjusted to account for the aggressive time step used by the model. The Δt used by the model is doubled each iteration. While this is not significant in the early seconds or minutes of the model, it is significant for cases which require longer periods of time for dispersion or evaporation. Therefore, we list both the final time and the previous time step. The estimated duration is then within the range of the two time steps.

To calculate a more accurate time to complete evaporation we recommend adding a subroutine which attempts to pinpoint the time of complete evaporation. This routine could return to the previous time step and advance one-half time step. The routine could continue this action until a predetermined accuracy is attained. The time required by the computational model to reach this accuracy would have to be a factor in implementing the subroutine.

Table 4.11 Time to Complete JP-8 Ground Evaporation from 300 m Release

15000 kg JP-8 Release, 300 m Release Height			
	-20°C	0°C	20°C
Mass Fraction	0.88028	0.62706	0.15705
Start Time, minutes	5.36	6.00	8.88
End Time, minutes (minus 1 timestep)	124420.21 (62281.94)	2070.57 (1042.18)	68.39 (39.17)
Estimated Duration	43 - 86 days	17 - 34 hours	30 - 60 minutes

Table 4.12 Time to Complete JP-8 Ground Evaporation from 500 m Release

15000 kg JP-8 Release, 500 m Release Height			
	-20°C	0°C	20°C
Mass Fraction	0.84305	0.53218	0.10008
Start Time, minutes	8.97	10.34	17.66
End Time, minutes (minus 1 timestep)	199993.62 (100071.43)	2565.85 (1291.88)	108.55 (64.31)
Estimated Duration	70 - 139 days	22 - 43 hours	47 - 91 minutes

Table 4.13 Time to Complete JP-8 Ground Evaporation from 1000 m Release

15000 kg JP-8 Release, 1000 m Release Height			
	-20°C	0°C	20°C
Mass Fraction	0.79131	0.39453	0.05812
Start Time, minutes	17.99	21.81	43.17
End Time, minutes (minus 1 timestep)	103158.23 (51658.55)	2057.72 (1043.93)	122.89 (84.34)
Estimated Duration	36 - 72 days	17 - 34 hours	41 - 80 minutes

Table 4.14 Time to Complete JP-8 Ground Evaporation from 1500 m Release

15000 kg JP-8 Release, 1500 m Release Height			
	-20°C	0°C	20°C
Mass Fraction	0.76514	0.32366	0.03571
Start Time, minutes	26.83	33.58	71.73
End Time, minutes (minus 1 timestep)	154861.16 (77516.16)	2039.92 (1040.64)	164.99 (119.40)
Estimated Duration	54 - 107 days	17 - 34 hours	48 - 93 minutes

Table 4.15 Time to Complete JP-8 Ground Evaporation from 3000 m Release

15000 kg JP-8 Release, 3000 m Release Height			
	-20°C	0°C	20°C
Mass Fraction	0.73564	0.24682	0.00422
Start Time, minutes	51.84	66.79	169.51
End Time, minutes (minus 1 timestep)	189977.25 (95082.31)	1613.92 (844.89)	264.76 (216.38)
Estimated Duration	66 - 132 days	13 - 26 hours	47 - 95 minutes

Table 4.16 Time to Complete JP-8 Ground Evaporation from 6000 m Release

15000 kg JP-8 Release, 6000 m Release Height			
	-20°C	0°C	20°C
Mass Fraction	0.72852	0.22768	0.00150
Start Time, minutes	95.09	118.15	326.40
End Time, minutes (minus 1 timestep)	104849.74 (52541.24)	2880.72 (1504.03)	411.76 (368.40)
Estimated Duration	36 - 73 days	23 - 46 hours	42 - 85 minutes

Table 4.17 Time to Complete JP-8 Ground Evaporation from 7500 m Release

15000 kg JP-8 Release, 7500 m Release Height			
	-20°C	0°C	20°C
Mass Fraction	0.72924	0.22849	0.00150
Start Time, minutes	113.85	138.73	352.07
End Time, minutes (minus 1 timestep)	106309.50 (53284.98)	2545.93 (1346.57)	434.13 (392.45)
Estimated Duration	37 - 74 days	20 - 40 hours	40 - 82 minutes

Table 4.18 Time to Complete JP-8 Ground Evaporation from 9000 m Release

15000 kg JP-8 Release, 9000 m Release Height			
	-20°C	0°C	20°C
Mass Fraction	0.73027	0.23027	0.00151
Start Time, minutes	131.00	157.13	366.68
End Time, minutes	198741.72 (99507.80)	2552.36 (1359.16)	455.43 (410.88)
Estimated Duration	69 - 138 days	20 - 40 hours	44 - 89 minutes

These results are generated using Equation 3.9 and Equation 3.11 in the subroutine for surface evaporation. We are assuming the fuel reaching the surface is in the form of small droplets which deposit on vegetation or similar surfaces. The results demonstrate that the release altitude is not a significant factor in the time to complete evaporation. The small mass fraction of jet fuel reaching the surface from a release altitude of 9000 meters evaporates essentially in the same time that a greater mass fraction of jet fuel reaching the surface from a 300 meter release.

As we discovered with the results in Table 4.4, the surface temperature has the greatest influence on evaporation. The time to complete evaporation for all cases when the surface temperature was 20°C was in the order of minutes, or roughly one hour. For 0°C, the time to complete evaporation was in the order of hours, or from one to two days. Finally, the time to complete evaporation for a surface temperature of -20°C was in the order of days and weeks.

The results for cases with a surface temperature of -20°C are suspect due to the large time step required and the actual capability of any heavy components evaporating at this temperature. Likewise, a time period of days and weeks is not supported by the constant environmental data file used by the model. For these long time periods, the model neglects the effect of diurnal temperature cycles, changing seasons, etc.

However, the results at 0°C and 20°C are more realistic and acceptable. At 20°C, both large mass fractions from low altitude releases and small mass fractions from high altitude releases will readily evaporate at the surface. Even at 0°C, the fuel reaching the surface can physically evaporate within several hours to a couple of days.

V. Summary, Conclusions, and Recommendations

5.1 Summary

Due to emergency situations or urgent mission-essential operational requirements, aircraft may occasionally be required to jettison unused jet fuel. Research has been accomplished to determine the impact of the jettisoned fuel when it reaches the surface. While previous work has resulted in the conclusion that the jettisoning of JP-4 jet fuel results in a negligible ground fall impact, the impact of jettisoning the lower volatile JP-8 jet fuel has not been characterized. Several efforts have been made to mathematically model the evaporation, advection, and dispersion of the plume of fuel as it travels to the surface. The locally developed AFIT Model, the Fuel Jettisoning Simulation Model, and the Fuel-Dumping Impact Assessment Model were evaluated and compared to assess the impact of jettisoning JP-8 jet fuel. Additionally, a modified version of the AFIT Model which includes surface evaporation was used to evaluate the time required to evaporate JP-8 jet fuel after it reaches the surface. While only an elementary step in this study, this thesis has provided some insight into the potential ground fall impact of JP-8 jettisoning.

5.2 Conclusions

Compared with the impact of JP-4 jet fuel, the jettisoning of JP-8 jet fuel does result in substantially more jet fuel reaching the surface. The surface and atmospheric temperatures greatly influence the evaporation rate the jet fuel. For JP-8, surface temperatures around 0°C and below result in a greater mass fraction of fuel reaching the surface. Our research indicated that release altitudes greater than 6000 meters did not decrease the mass fraction of fuel remaining when it reached the surface. Although dispersion, assuming a standard atmospheric profile with wind shear, will increase as the release altitude is increased, the resulting concentrations are not reduced enough to recommend altering the recommended jettison altitude of 20,000 feet (6000 meters). For surface temperatures above 0°C and assuming reasonable weather conditions, JP-8 jet fuel that does reach the surface will evaporate within a few hours to a couple of days.

Therefore, the significance of the impact of JP-8 jet fuel jettisoning is dependent upon several factors; altitude, surface temperature, and weather conditions. Assuming a controlled release above 6000 meters and a non-freezing surface temperature, the impact of JP-8 jet fuel should be negligible. For lower release altitudes and temperatures, the impact may be significant. Therefore, these models can be used to estimate the impact and prepare an adequate response.

5.3 Recommendations

An early objective of this thesis was to accomplish an independent assessment of the Fuel Jettisoning Simulation Model (FJSIM) developed by Continuum Dynamics, Incorporated under contract for Armstrong Laboratory. However, the research-grade code to which we had access was not flexible enough for the cases we wanted to run. We recommend that the evaluation of FJSIM be accomplished when a more advanced version of the model code is available.

We recommend that the AFIT Model be modified to include a more accurate method to calculate the standard deviation of the horizontal wind direction, σ_θ. The AFIT Model can also use the real upper air data to calculate the altitude of the planatary boundary layer and start the dispersion calculations at this altitude rather than the jettison altitude. These modifications should improve the dispersion calculations of the AFIT Model.

Experimentally, more research is required into the droplet distribution, evaporation, and other physical characteristics of JP-8 jet fuel. JP-8 characteristics are often interpolated from JP-4 for most of the research cited. Specific research on the characteristics of JP-8 will improve this effort. Research of the chemical reactions in the atmosphere due to evaporation of the volatile components and research into the toxicity of the jet fuel at various phases of the fuel free fall and at ground fall would also improve the understanding and effectiveness of this modeling effort.

As experimental data is provided, the mathematical model can be improved and expanded to include this information. Specifically, the study of surface evaporation requires additional research to characterize the physics and model the evaporative process. This characterization assumes that the JP-8 jet fuel is deposited on vegetation or similar surface and is not quickly absorbed into soil or other substrate. However, experimental studies of JP-8 evaporation demonstrated that evaporation was also the major removal process of JP-8 in the aquatic environment (Dean-Ross, et al., 1992:225). While this thesis does not address evaporation of jet fuel contamination in an aquatic environment, evaporation in that environment is also a key process in the determination of the significance of the JP-8 jet fuel contamination. Specific research into surface evaporation must be accomplished to more accurately characterize the evaporation process. Additionally, the impact of sunlight and diurnal temperature variations on surface evaporation must also be considered.

Another process to research and implement is biodegradation (Leahy, 1990). In a study of the environmental fate of JP-8 in aquatic and terrestrial environments, it was noted that biodegradation contributed to the removal of JP-8 from soil, but not from the purely aquatic environment. It was also noted that nitrogen-rich or treated locations accelerated the removal of hydrocarbons suggesting that providing conditions to enhance biodegradation will increase the rate of removal of JP-8 from the terrestrial environment (Dean-Ross, et al., 1992:228).

Finally, the study of the management application of these models can be expanded. This thesis indicated that operational units could use the models to select the optimum release altitude and location based on the current weather conditions. The model could be implemented by aircrew using on-board computers or by flight operations personnel on the ground. After a jettison event, the model could also be used by environmental managers and response personnel to determine the significance of the impact and responses needed. A review of the management applicability of these models would improve the useability of the models.

Appendix A.

Fuel Jettisoning Procedures from Flying Operations, KC-135 Operations (Department of the Air Force. MCI 11-235. Washington: HQ USAF, 1 July 1995.)

18. Fuel Jettisoning Procedures. Fuel jettison is limited to the minimum necessary for safe and effective flight operations.

18.1. Jettison fuel only under the following circumstances:

18.1.1. Aircraft emergency. Immediate reduction of gross weight is critical to safe recovery of the aircraft.

18.1.2. Urgent Operational Requirements. Immediate reduction of gross weight is necessary to meet urgent operational mission tasking.

18.2. Units will establish jettison areas and procedures to minimize the impact of fuel jettisoning into the atmosphere.

18.2.1. Units will initiate AF Form 813, Request for Environmental Impact Analysis and submit to the base environmental coordinator.

18 2.2. Designate jettison areas off published airways and avoid urban areas, agricultural regions, and water supply sources.

18.2.3. Avoid circling descents.

18 3. Use jettison altitudes above 20,000' AGL to the maximum extent possible.

18.4. Use designated jettison areas to the maximum extent possible except when safety of flight would be compromised.

18.5. If jettison is accomplished, record all pertinent data to include flight conditions, altitude, airspeed, air temperature, wind direction and velocity, type and amount of fuel, aircraft type and position at time of jettison, time and duration of jettison activity, and reason jettison was accomplished.

18.5.1. Retain the information in 18.5. for six months as documentation in the event of claim against the government resulting from the fuel jettison. Unit CC will determine the actual place of storage of this information.

Appendix B. Clewell's Fuel Component Models

Table B-1 Clewell's 33-component model for JP-4 (1981:5)

Component	Volume Fraction	Molecular Weight	Boiling Point (K)	Density at 20°C (kg/m^3)
C5 hydrocarbons	0.039	72.2	301.1	620.0
C6 paraffins	0.081	86.2	333.4	660.0
C6 cycloparaffins	0.021	84.2	353.9	780.0
Benzene	0.003	78.1	353.2	880.0
C7 paraffins	0.094	100.2	364.9	690.0
C7 cycloparaffins	0.071	98.2	374.1	770.0
Toluene	0.007	92.1	383.9	870.0
C8 paraffins	0.101	114.2	390.9	700.0
C8 cycloparaffins	0.074	112.2	397.4	780.0
C8 aromatics	0.016	106.2	412.2	870.0
C9 paraffins	0.091	128.3	415.6	720.0
C9 cycloparaffins	0.043	126.2	427.6	800.0
C9 aromatics	0.024	120.2	438.4	880.0
C10 paraffins	0.073	142.3	432.8	720.0
C10 cycloparaffins	0.037	140.3	444.1	800.0
C10 aromatics	0.018	134.2	450.2	860.0
Napthalene	0.002	128.2	491.1	1030.0
C11 paraffins	0.048	156.3	469.1	740.0
C11 cycloparaffins	0.025	154.3	469.6	800.0
Dicycloparaffins	0.034	150.3	474.1	890.0
C11 aromatics	0.011	148.2	478.1	860.0
C11 napthalenes	0.002	142.2	517.8	1020.0
C12 paraffins	0 028	170.3	489.4	750.0
C12 cycloparaffins	0.012	168.3	484.1	800.0
C12 aromatics	0.005	162.3	489.1	860.0
C12 napthalenes	0.002	156.2	541.1	1000.0
C13 paraffins	0.011	184.4	508.6	760.0
C13 cycloparaffins	0.004	182.4	498.1	800.0
C13 aromatics	0.001	176.3	507.1	870.0
C14 hydrocarbons	0.002	198.4	526.9	760.0
C15 hydrocarbons	0.001	212.4	543.8	770.0
Tricycloparaffins	0.018	192.4	563.1	940.0
Residual hydrocarbons	0.001	202.3	666.1	1270.0

Table B-2 Clewell's 27-component model for JP-8 (1981:6)

Component	Volume Fraction	Molecular Weight	Boiling Point (K)	Density at 20°C (kg/m^3)
C8 paraffins	0.003	114.2	391.1	700.0
C8 cycloparaffins	0.002	112.2	397.1	780.0
C8 aromatics	0.001	106.2	412.1	870.0
C9 paraffins	0.024	128.3	415.1	720.0
C9 cycoloparaffins	0.015	126.2	427.1	800.0
C9 aromatics	0.010	120.2	438.1	880.0
C10 paraffins	0.056	142.3	433.1	720.0
C10 cycloparaffins	0.035	140.3	444.1	800.0
C10 aromatics	0.023	134.2	450.1	860.0
C11 paraffins	0.087	156.3	469.1	740.0
C11 cycloparaffins	0.033	154.3	469.1	800.0
Dicycloparaffins	0.031	152.3	474.1	890.0
C11 aromatics	0.036	148.2	478.1	860.0
C12 paraffins	0.108	170.3	489.1	750.0
C12 cycloparaffins	0.080	166.3	494.1	880.0
C12 aromatics	0.046	162.3	489.1	860.0
C13 paraffins	0.115	184.4	508.1	760.0
C13 cycloparaffins	0.085	182.4	498.1	800.0
C13 aromatics	0.049	176.3	507.1	870.0
C14 paraffins	0.059	198.4	527.1	760.0
C14 cycloparaffins	0.044	192.4	563.1	940.0
C14 aromatics	0.025	186.3	568.1	1030.0
C15 paraffins	0.014	212.4	544.1	770.0
C15 cycloparaffins	0.010	206.4	573.1	900.0
C15 aromatics	0.006	200.4	578.1	950.0
C16 hydrocarbons	0.002	226.4	560.1	770.0
Residual hydrocarbons	0.001	202.3	666.1	1270.0

Appendix C. Sample AFIT Model Results (case.msg)

Segments of the message output file for the case of JP-8 jettisoned at 6000 meters with a wind direction of 270° and a aircraft orientation of 180° are presented below. The entire output file was over 90 pages long in its original format.

```
#>=====================================
#> AFIT Fuel Jettison Model Version  1.40 =
#>=====================================
#
# CURRENT TIME: Sat Aug 26 14:22:12 1995
#
# ENVIRONMENTAL PROFILE
# ====================
#
# Altitude       Pressure       Temperature
# --------       -------- -----------
#     0.0             101325.0         293.1
#   500.0              95557.0         289.9
#  1000.0              90058.0         286.6
"
DATA REMOVED
"
# 10000.0              27126.0         228.1
#
#
#          East/West      North/South
# Altitude       Wind Speed    Wind Speed
# --------       ----------    ----------
#     0.0              4.1            0.0
# 10000.0              4.1            0.0
#
#
# RELEASE DATA
# ===========
#
```

```
# Aircraft data
# -------------
# Altitude          =  6000.0 meters
# Airspeed          =   175.0 m/s
# Heading           =   180.0 degrees
# Jettison Rate     =    50.0 kg/s
# Jettison Duration =   300.0 s
#
# Plume data
# ----------
# Begin Latitude  =  39.54000 degrees
#       Longitude = -84.12000 degrees
# End   Latitude  =  39.06778 degrees
#       Longitude = -84.12000 degrees
#
# Plume mass      =    15000.0 kg
# Plume length    =    52500.0 m
# Plume width     =      100.0 m
# Mean drop diameter =     270.0 microns
# At groundfall
# droplet disc ratio =   0.05000
#
#
# DROPLET MODEL TIME (minutes)       =    0.00000
#
# DROPLET COMPOSITION
# ===================
#
# Fuel Type          = JP-8 (Clewell)
# Number of components = 27
#
#                          Volume  Molecular  Boiling  Reference
# Component                Percent  Weight     Point    Density
#
=====================================================================
===================
# C8 paraffins          0.003   114.2    391.1    700.0
# C8 cycloparaffins       0.002   112.2    397.1    780.0
# C8 aromatics           0.001   106.2    412.1    870.0
//
```
DATA REMOVED

```
//
# C16 hydrocarbons           0.002   226.4    560.1    770.0
# Residual hydrocarbons      0.001   202.3    666.1   1270.0
#
# DROPLET PHYSICAL PROPERTIES AND DYNAMICS
# =====================================
#
# Diameter           =  270.0 microns
# Initial Mass       = 8.5433e-09 kilograms
# Density of mixture =  829.0 kg/m^3
# Temperature        =  269.4 K
# Altitude           = 6000.0 meters
# East/West speed    =    0.0 m/s
# North/South speed  = -175.0 m/s
#

#>
# DROPLET MODEL TIME (minutes)        =    0.00000
# Altitude (meters)              = 6000.00000
# Diameter (microns)               =  270.00000
# Mass fraction                  =    1.00000
#>
# PLUME MODEL TIME (minutes)          =    0.00000
# Kx (m^2/s)                     =  100.00000
# Ky (m^2/s)                     =  111.21991
# x step size (meters)             =      525.0
# y step size (meters)             =        1.0
# Model Maximum Concentration (kg/m^2) = 1.49445e-03
# Line Source Maximum (kg/m^2)        = 1.63869e-03
# Relative Error                 = 8.80208e-02
# Cross section concentration (kg/m^2) = 2.85991e-01
# Plume width (meters)               =       52.0
#>
# DROPLET MODEL TIME (minutes)        =    0.01667
# Altitude (meters)              = 5998.86373
# Diameter (microns)               =  269.99999
# Mass fraction                  =    1.00000
#>
# PLUME MODEL TIME (minutes)          =    0.01667
# Kx (m^2/s)                     =  100.00000
# Ky (m^2/s)                     =  111.21991
```

x step size (meters) = 525.0
y step size (meters) = 2.0
Model Maximum Concentration (kg/m^2) = 1.48595e-03
Line Source Maximum (kg/m^2) = 1.37263e-03
Relative Error = 8.25511e-02
Cross section concentration (kg/m^2) = 2.85979e-01
Plume width (meters) = 52.0
#>
//
DATA REMOVED
//
DROPLET MODEL TIME (minutes) = 1.27524
Altitude (meters) = 5914.18778
Diameter (microns) = 260.95544
Mass fraction = 0.92109
#>
PLUME MODEL TIME (minutes) = 1.27524
Kx (m^2/s) = 100.00000
Ky (m^2/s) = 111.21991
x step size (meters) = 525.0
y step size (meters) = 8.0
Model Maximum Concentration (kg/m^2) = 7.16600e-04
Line Source Maximum (kg/m^2) = 6.82078e-04
Relative Error = 5.06135e-02
Cross section concentration (kg/m^2) = 2.63408e-01
Plume width (meters) = 80.0
#>
//
DATA REMOVED
//
DROPLET MODEL TIME (minutes) = 90.71853
Altitude (meters) = 2352.18583
Diameter (microns) = 130.58163
Mass fraction = 0.12525
#>
PLUME MODEL TIME (minutes) = 90.71853
Kx (m^2/s) = 100.00000
Ky (m^2/s) = 111.21991
x step size (meters) = 525.0
y step size (meters) = 64.0
Model Maximum Concentration (kg/m^2) = 1.29619e-05

```
# Line Source Maximum (kg/m^2)        = 1.29388e-05
# Relative Error                      = 1.79024e-03
# Cross section concentration (kg/m^2) = 3.57939e-02
# Plume width (meters)                =       640.0
#>
# DROPLET MODEL TIME (minutes)        =   325.71853
# Altitude (meters)                   =     1.17644
# Diameter (microns)                  =    26.82381
# Mass fraction                       =     0.00150
#>
# PLUME MODEL TIME (minutes)          =   325.71853
# Kx (m^2/s)                          =   100.00000
# Ky (m^2/s)                          =   111.21991
# x step size (meters)                =       525.0
# y step size (meters)                =        64.0
# Model Maximum Concentration (kg/m^2) = 8.20828e-08
# Line Source Maximum (kg/m^2)        = 8.20649e-08
# Relative Error                      = 2.18292e-04
# Cross section concentration (kg/m^2) = 4.29210e-04
# Plume width (meters)                =      1280.0
#>
# DROPLET MODEL TIME (minutes)        =   326.39605
# Altitude (meters)                   =     0.00000
# Diameter (microns)                  =    26.81979
# Mass fraction                       =     0.00150
#>
# PLUME MODEL TIME (minutes)          =   326.39605
# Kx (m^2/s)                          =   100.00000
# Ky (m^2/s)                          =   111.21991
# x step size (meters)                =       525.0
# y step size (meters)                =        64.0
# Model Maximum Concentration (kg/m^2) = 8.19626e-08
# Line Source Maximum (kg/m^2)        = 8.19447e-08
# Relative Error                      = 2.17638e-04
# Cross section concentration (kg/m^2) = 4.29026e-04
# Plume width (meters)                =      1280.0
#
# DROPLET MODEL TIME (minutes)        =   326.39605
#
//
```

DATA REMOVED

```
//
#
# EVAPORATION AFTER GROUNDFALL
# ASSUMING DISC RATIO =     0.05000
#
#>
# DROPLET MODEL TIME (minutes)        =  327.75109
# Altitude (meters)              =    0.00000
# Diameter (microns)               =   80.10320
# Mass fraction                 =    0.00150
#>
# DROPLET MODEL TIME (minutes)        =  330.46117
# Altitude (meters)              =    0.00000
# Diameter (microns)               =   78.40081
# Mass fraction                 =    0.00141
#>
//
```

DATA REMOVED

```
//
# DROPLET MODEL TIME (minutes)        =  368.40235
# Altitude (meters)              =    0.00000
# Diameter (microns)               =   47.48221
# Mass fraction                 =    0.00031
#>
# DROPLET MODEL TIME (minutes)        =  411.76369
# Altitude (meters)              =    0.00000
# Diameter (microns)               =    0.00000
# Mass fraction                 =    0.00000
#
# CURRENT TIME: Sat Aug 26 14:27:04 1995
#
#>==============================
#> END AFIT Fuel Jettison Model =
#>==============================
```

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Vita

Capt Jeffrey M. Todd [redacted] After graduating from Riverdale High School in 1984, he attended Vanderbilt University in Nashville, Tennessee on an Air Force ROTC scholarship. He graduated with a Bachelor of Engineering degree in Civil and Environmental Engineering in 1988 and received his United States Air Force commission.

His first assignment was to the 305th Civil Engineering Squadron at Grissom AFB, Indiana as Chief of CE Readiness. In 1990, Capt Todd was assigned to the 8th Civil Engineering Squadron at Kunsan Air Base, South Korea as the Deputy Chief of Design and later the Base Environmental Coordinator. In 1991, he was assigned to the 513th Civil Engineering Squadron (later realigned as the 100th Civil Engineering Squadron) at Royal Air Force Mildenhall, United Kingdom as the Environmental Flight Commander. While stationed at RAF Mildenhall, he was temporarily assigned to Headquarters, Operation Provide Comfort at Incirlik Air Base, Turkey. In 1994, Capt Todd began his studies at the School of Engineering, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio for the Master of Science degree in Engineering and Environmental Management.

Capt Todd is married to the former Ms. Valerie Smith. He and his wife have two daughters, Olivia and Caroline.

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Work has been accomplished to determine the impact of jettisoned fuel when it reaches the surface. While previous work indicates that jettisoning JP-4 jet fuel results in a negligible ground fall impact, the impact of jettisoning lower volatile JP-8 jet fuel has not been thoroughly characterized. Several efforts have been made to mathematically model the evaporation, advection, and dispersion of the plume of fuel as it travels to the surface. The AFIT Fuel Jettisoning Model, the Fuel Jettisoning Simulation Model, and Fuel-Dumping Impact Assessment Model were evaluated and compared to assess the impact of jettisoned JP-8 jet fuel. Additionally, the AFIT Model has been modified to include surface evaporation to evaluate the time required to evaporate JP-8 jet fuel after it reaches the surface. While JP-8 jet fuel does impact the surface more than JP-4 jet fuel, the mass of JP-8 jet fuel remaining from releases at altitudes greater than 6000 meters and at surface temperatures greater than 0°C can evaporate within hours. We conclude that the recommended jettison release altitude for large body aircraft of 6000 meters is adequate.

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