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Atmospheric Dispersion Modeling Tools for Hanford Tank Farms Applications

August 2017

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Pacific Northwest National Laboratory
Richland, Washington 99352

Revision History

Revision Number	Effective Date	Description of Change
0	10/7/2016	Initial Issue.
1	08/31/2017	Incorporate two additional models (AIHA Near and Mid-Field Plume, NIST FDS) per WRPS Requisition #297898.

Summary

The Hanford tank farms have 177 underground tanks distributed across 18 tank farms that contain radioactive and chemical wastes from the Cold War era plutonium production missions. These tank farms contain either single-shell tanks equipped with passive breather filters on 1.0- to 1.5-m-tall stacks, or double-shell tanks that are actively ventilated through 6- to 15-m-tall stacks. Chemical vapor emissions have been a concern at the tank farms despite efforts to understand and manage potential exposure to vapor emissions. An increase in reported symptoms suspected to be related to chemical vapor exposures during early 2014 led to a focused revitalization of the chemical vapors hazard management program to account for evolving conditions in the tank farms. The chemical vapors hazard management program is administered and implemented by Washington River Protection Solutions (WRPS), the U.S. Department of Energy's (DOE) Tank Operations Contractor. WRPS-led revitalization efforts included establishment of an independent Hanford Tank Vapor Assessment Team (TVAT) to examine hazardous chemical vapors management, related worker protection measures, and recommended actions. The recommendations of the TVAT¹ as well as other vapor control improvements are being implemented in a phased approach within WRPS' chemical vapors hazard management program² and include a series of projects and activities being executed by multi-disciplinary and multi-organization teams.

The chemical vapors hazard management program is guided by DOE's Integrated Safety Management System (ISMS), which defines the policies, objectives, and approach to ensuring protection of the public, worker, and the environment.³ The five ISMS core functions, shown in Figure S.1, define the structure for planning and implementing work activities that pose a potential hazard. The core ISMS function of "analyze hazards" is a focus of several key improvements to the chemical hazards management program, and is represented by a series of projects and activities aimed at better identification and understanding of the vapor hazards. These activities include a) extensive headspace, source (e.g., stack or breather filter), and area characterization and monitoring; b) bench- and pilot-testing of a real-time vapor monitoring and detection system for potential tank farm deployment; c) updating the list of Chemicals of Potential Concern and corresponding exposure action levels to ensure the most complete and recent tank farm data and chemical hazard information is being used; d) analysis of dispersion modeling methods to improve understanding of vapor plume migration and aerial extent of potential exposure; and e) identification of chemical vapor leading indicators that can provide readily measurable early indication of vapor emissions ahead of other, more difficult to measure chemical vapors.



Figure S.1. Integrated Safety Management System

¹ Wilmarth WR, MA Maier, TW Armstrong, RL Ferry, JL Henshaw, RA Holland, MA Jayjock, MH Le, JC Rock, and C Timchalk. 2014. *Hanford Tank Vapor Assessment Report*. SRNL-RP-2014-00791, Rev. 0, Savannah River National Laboratory, Aiken, SC.

² WRPS. 2015. *Implementation Plan for Hanford Tank Vapor Assessment Report Recommendations*. Washington River Protection Solutions. Washington River Protection Solutions, Richland, WA. <http://wrpstoc.com/wp-content/uploads/2015/02/WRPS-1500142-Enclosure.pdf>

³ DOE. 2008. *Integrated Safety Management System Description*. U.S. Department of Energy, Office of Environmental Management Headquarters, Washington, D.C.

Pacific Northwest National Laboratory (PNNL) is supporting WRPS' chemical vapors hazard management program improvement efforts with research, analysis, development, testing, and technical support in several of these key areas focused on better identification and understanding of the vapor hazards. The effort described in this report is one part of an overall vapors program at PNNL, specifically addressing dispersion modeling methods. This project, performed during fiscal year (FY) 2016, had three main tasks:

1. Overview of different types of dispersion models
2. Evaluation of specific models for four application areas
3. Review of a parametric dispersion study

Tasks 1 and 2 describe four classes of dispersion models (plume, puff, particle, and computational fluid dynamics [CFD]) and four modeling application areas (real-time response, worker safety and emergency planning, regulatory, and engineering and research). A model ranking method was applied to rank selected dispersion models. These models are either commonly used in each application area or are models that are currently in use at the tank farms. During FY 2017, this report was revised to add two models that are used for the tank farms, and relevant updates were also made to this text.

The top ranking worker safety and emergency response models were

- Fire Dynamics Simulator (FDS) (a CFD model optimized for low-speed, thermally driven flow)
- CALPUFF (a long-range regulatory puff model)
- QUIC (a building-aware particle model designed for emergency response and planning)
- APGEMS (a puff model that uses real-time data from the Hanford Site, designed for emergency response).

The CALPUFF, QUIC, and APGEMS models were also ranked at the top for the real-time response model application. Although these models ranked high compared with other models in these application areas, the strengths and limitations of the class of model (plume, puff, particle, or CFD), as well as the strengths and limitations of the specific model in question for each application, must be evaluated. Specific modeling goals, including the important spatial scales, time scales, and other model features, should be examined carefully when selecting specific models for use.

Seven atmospheric dispersion models are (or have recently been) used at the Hanford tank farms for various purposes. AERMOD, a regulatory plume model, is used both for regulatory needs as well as for engineering evaluations, such as evaluation of stack height impacts. A CFD code called CFX has also been used to evaluate stack heights and to explore case studies surrounding reported exposures. EPIcode is a plume model used in worker safety and emergency response, and is a DOE toolbox model. A model that is referred to in this report as the AIHA-Eddy model is an industrial hygiene puff model used to evaluate releases within 10 m to assess vapor control zones and vapor reduction zones. Another AIHA model, referred to as AIHA-Plume in this report, is used to evaluate continuous stack emissions for vapor control zones and vapor reduction zones. Additional efforts to evaluate sensor placement needs based on exposure risk have used the CFD code called the Fire Dynamics Simulator, or FDS. Finally, SAFER is a commercial data retrieval, data display, and modeling package that was installed at the tank farms for evaluation as part of pilot-scale testing activities. In general, these models are implemented in applications that are reasonable for that model. Although other models may rank higher in this general evaluation, each model meets the specific objectives of specific tank farms modeling applications for which they are used.

Table S.1 presents a summary of models that are recommended for a selection of specific model applications from the tank farms. This illustrates that model recommendations for modeling needs with specific spatial scales and model goals may differ from the results of ranking based on broad application areas. CALPUFF was ranked highly; however, the model is intended for distances of tens to hundreds of kilometers, which is beyond the distance of interest for these specific tank farm applications. Gaussian models are not accurate for the nearest 100 m from a source, so for problems in that spatial scale, models such as QUIC and CFD are recommended. The puff model APGEMS is also recommended based on its strengths in fast setup, fast runtimes, and ease of operation. The approximate result that APGEMS produces at distance within 100 m from the source may be of value in AOP-015 investigations and emergency planning.

Table S.1. Model Recommendations for Tank-Farm Specific Applications

Application Area	Recommended Model(s)
Environmental Compliance	AERMOD
Establish Vapor Control Zones	QUIC, CFD (e.g., FDS)
Establish Unrestricted Work Boundaries	QUIC, CFD (e.g., FDS)
Stack Height Evaluation	AERMOD, CFD (e.g., FDS)
AOP-015 Investigations	APGEMS, QUIC, CFD (e.g., FDS)
Sampling Location Strategy	QUIC, CFD (e.g., FDS)
Emergency Planning	EPIcode, APGEMS, QUIC, CFD (e.g., FDS)

A model validation study adds significant value as part of implementing a dispersion model for operational use at the tank farms. Executing a tracer study at or near the tank farms provides ground-truth data to illustrate the strengths and weaknesses of specific models for specific test cases. A general review of model features like that presented in this work provides an overview of the suitability of the model, but following this with site-specific model validation efforts gives users detailed information about the model capability. This report provides a general overview of such a tracer study, since a successful tracer study for model evaluation requires detailed planning to achieve specific objectives.

Task 3 assessed the need to update a parametric dispersion study (Droppo 2004¹) with the latest U.S. Environmental Protection Agency recommended dispersion model. Atmospheric dispersion is treated very differently between the stability class approach used by Droppo (2004) and the Industrial Source Complex (ISC) model and the boundary layer similarity approach within AERMOD. As a result, the Droppo work and ISC simulations compared within a factor of four, but the AERMOD simulations had large differences that diverged with downwind distance. These large differences between the models are a result of these fundamental differences in the model inputs. The attempt to map the Droppo (2004) stability classes to AERMOD boundary layer similarity input results in a comparison of individual model realizations. AERMOD is designed to produce statistically averaged results, and is not meant to be used for case study evaluations. Therefore, a meaningful conclusion cannot be made from this comparison.

Alternatively, developing an input file with several years of onsite data to develop the statistical output that is the intended AERMOD output would be a more appropriate method to evaluate the need to update the Droppo work. The added value of a rigorous study with AERMOD is that the results can be analyzed

¹ Droppo JG. 2004. *Characterization of the Near-Field Transport and Dispersion of Vapors Released from the Headspace of Hanford Site Underground Storage Tanks*. PNNL-14767, Pacific Northwest National Laboratory, Richland, WA.

for additional details, such as the frequency of occurrence of low-dispersion conditions, peak concentrations, and typical concentrations. Note, however, that the peak concentrations produced by a model such as AERMOD represent hourly averaged values, and peak concentrations at higher temporal resolutions may be an order of magnitude higher than these hourly values. Additionally, certain meteorological phenomena that may result in the transport of nearly undiluted headspace concentrations are not captured by plume models. These conditions include cold winter mornings with low inversions as well as hot summer days with large thermal eddies.

Based on the model ranking and evaluation of atmospheric dispersion modeling needs at the tank farms, recommendations for future work to implement appropriate modeling tools for tank farms include the following:

- Consider the operational use of APGEMS at the tank farms to regularly estimate plume location based on estimates of release positions and emission rates. Since this model is developed by PNNL, tank-farm-specific meteorological stations and source term libraries specific to the tank farms can be incorporated to help improve plume estimates.
- Incorporate a high spatial- and temporal-resolution model such as FDS or QUIC for applications within 100 m of a source.
- If a comparison with the Droppo (2004) work is needed, this should be performed with an AERMOD study with 5 years of local meteorological data for selected release locations to compare the concentration output. Although this type of AERMOD simulation has been performed by WRPS as part of regulatory requirements and engineering and research efforts, the output has not been analyzed for a parametric study comparison, nor has it been evaluated for the frequency of occurrence of potentially low-dispersion conditions.
- Discontinue the use of SAFER software, based on the result of pilot-scale testing of SAFER for the tank farms.
 - Other models that are selected for tank farms use (in lieu of SAFER) should be accompanied by clear documentation of the dispersion model limitations.
- Develop a limited wind library with CFD software to evaluate the impact of structures on concentrations, and to evaluate the utility of wind libraries (i.e., pre-computed wind fields) to quickly produce concentration estimates for real-time response applications.
 - The model simulations performed by Kenexis for sensor placement needs may be used for wind library evaluations as well.
- Assess the needs and goals of a tracer study to evaluate a model or models selected for use at the tank farms. Design and execute a tracer study based on the model(s) under evaluation and the specific goals of using these models.

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Acronyms and Abbreviations

200E	200 East Area of the Hanford Site
200W	200 West Area of the Hanford Site
ADAPT/LODI	Atmospheric Data Assimilation and Parameterization Tool / Lagrangian Operation Dispersion Integrator
AERMOD	AMS/EPA Regulatory Model
AIHA	American Industrial Hygiene Association
ALOHA	Areal Locations of Hazardous Atmospheres
APGEMS	Air Pollutant Graphical Environmental Modeling System
ARCON96	Atmospheric Relative Concentrations in Building Wakes computer code
CALPUFF	California Puff Model
CAM	Consequence Assessment Modeling
CC	centerline concentration
CFD	computational fluid dynamics
CPU	central processing unit
DES	detached eddy simulation
DOE	U.S. Department of Energy
EOC	Emergency Operations Center
EPA	U.S. Environmental Protection Agency
EPIcode	Emergency Prediction Information code
FDS	Fire Dynamics Simulator
FY	fiscal year
GC	ground-level concentration
GPU	graphic processor unit
GUI	graphical user interface
HEPA	high-efficiency particulate air
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
ISC	Industrial Source Complex (model)
ISMS	Integrated Safety Management System
LANL	Los Alamos National Laboratory
LES	large eddy simulation
LLNL	Lawrence Livermore National Laboratory
MFiX	Multiphase Flow with Interphase Exchange
NARAC	National Atmospheric Release Advisory Center
NETL	National Energy Technology Laboratory
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration

NRC	U.S. Nuclear Regulatory Commission
PAC	Protective Action Criteria
PBF	passive breather filter
PG	Pasquill-Gifford
PNNL	Pacific Northwest National Laboratory
QA	quality assurance
QUIC	Quick Urban & Industrial
ROM	reduced order model
SCAPA	DOE Subcommittee on Consequence Assessment and Protective Actions
SCIPUFF	Second-Order Closure Integrated Puff Model
TVAT	Hanford Tank Vapor Assessment Team
UWB	unrestricted work boundary
VCZ	vapor control zone
VRZ	vapor reduction zone
WRPS	Washington River Protection Solutions
WTP	Hanford Tank Waste Treatment and Immobilization Plant

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1.0 Introduction

The Hanford Site, located in south-central Washington State, was a site selected under the Manhattan Project for the production of plutonium for nuclear weapons. Today, the site is primarily an environmental cleanup project. Some of the biggest cleanup challenges on the site are large underground storage tanks (with capacities of 50,000 to over 1 million gallons) of radioactive and chemical waste mixtures that were produced during processing of nuclear materials for U.S. weapons programs during the Cold War era. These underground storage tanks are either single-shell, passively ventilated vessels, or double-shell, actively ventilated vessels. These 177 tanks are distributed among 7 tank farms in the Hanford 200 West (200W) Area and 11 tank farms in the 200 East (200E) Area. Figure 1.1 shows an aerial photograph of the Hanford Central Plateau, identifying individual tank farms with pink polygons. The two 200 Areas cover a space that is about 10 km wide, encompassing several other facilities, including those that have been decommissioned, are in the process of closure, are support facilities for site operations, or are construction projects for waste processing.

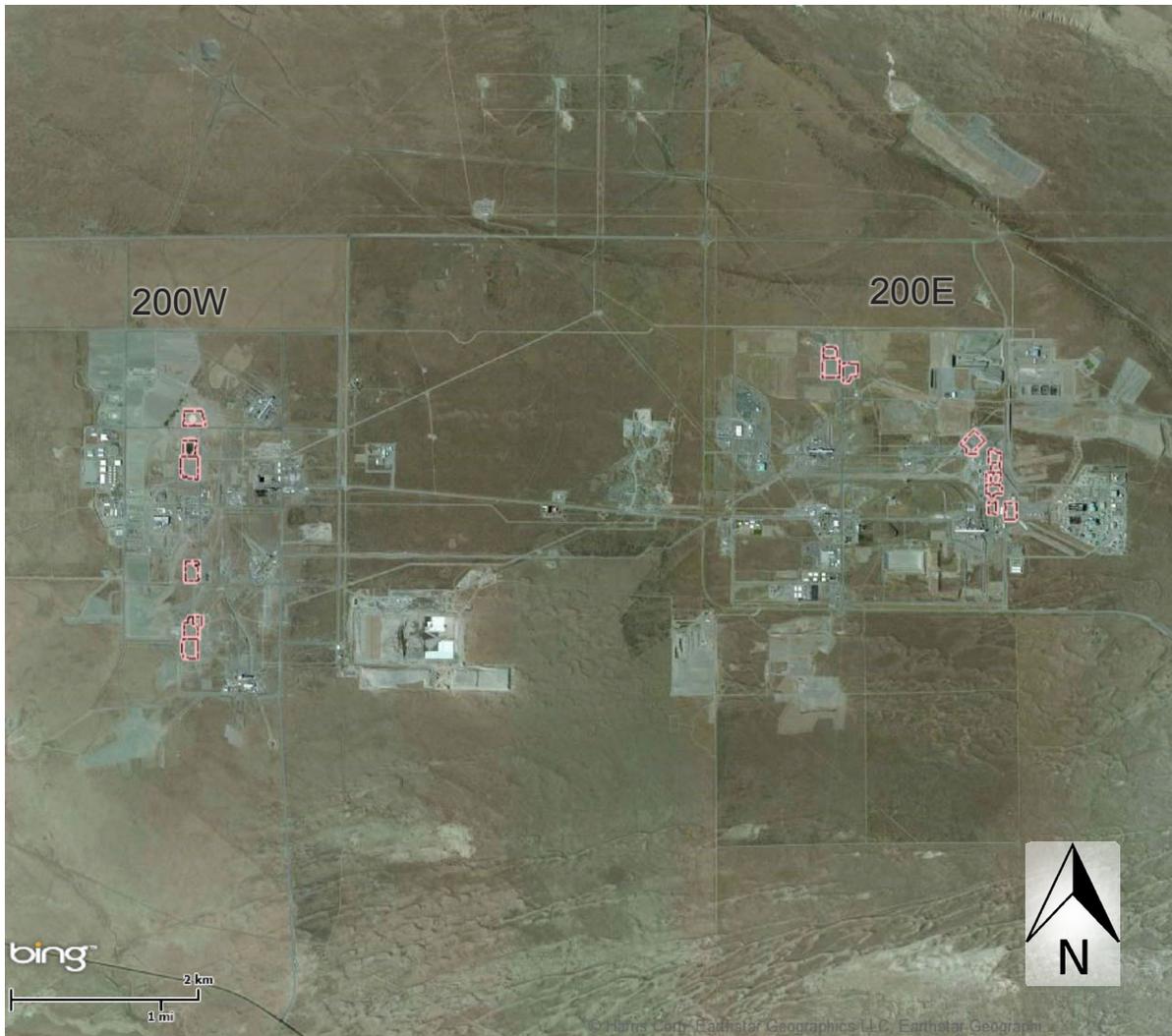


Figure 1.1. Aerial Photograph of the Hanford Site Central Plateau with the 200E and 200W Tank Farms (pink outlines)

Figure 1.2 shows 8 of the 11 tank farms in the 200E Area to illustrate the relevant distances within and between tank farms, as well as the other facilities in the area. The fence lines of most tank farms are between 100 and 200 m long on a side, and many tank farms are clustered adjacent to each other. Tank farms are labeled with a number and letter(s), such as 241-C and 241-AN. The tank farms are often referenced by their letter designations, a convention adopted in this report.



Figure 1.2. Aerial Photograph of the 200E Tank Farms (missing B farms, located to the northwest)

Each tank farm is a collection of either single-shell or double-shell tanks. Although the ground surface is flat within the fence lines of a tank farm, the surface is often raised or lowered by several meters compared with the area just outside of the tank farm (5 to 10 m from the fence line).

Of the 177 total tanks, 149 are single-shell tanks. The single-shell tanks are equipped with passive breather filters (PBFs), which are effectively short stacks, between 1.0 and 1.5 m tall, with a cylindrical high-efficiency particulate air (HEPA) filter installed at the top, covered by a sheet metal cap to protect

the filter from wind and rain. There is a single PBF for each single-shell tank, but there are connections between headspaces in adjacent tanks through underground piping. Figure 1.3 shows a PBF located in the A Tank Farm. The construction cranes in the background of this photo are at the Hanford Tank Waste Treatment and Immobilization Plant (WTP), about 800 m east-southeast of A Farm. These PBFs emit tank headspace vapors based on air temperature, barometric pressure, winds, or tank activities as described by Huckaby et al. (2004).



Figure 1.3. Photograph of a Passive Breather Filter in the A Tank Farm in the 200E Area (looking southeast)

Double-shell tanks are newer tanks that were built to receive waste from the older (and failing) single-shell tanks. As their name implies, the double-shell tanks have a secondary shell to contain potential leaks from the inner shell, preventing waste material from entering the environment. The headspaces of the double-shell tanks within a single tank farm are connected by underground ducting and are actively ventilated through a relatively tall stack. Older stacks are about 6 m tall, while newer stacks are up to 15 m tall. Figure 1.4 is a photograph of a large portion of the AP Farm, taken near the southwest corner of the farm. Note the elevation difference between the foreground, outside the fence, and the tank farm, within the fence. In the case of both single-shell and double-shell tanks, concrete pits are above the tank and a concrete block is on top. In Figure 1.4, these pits are covered by white tents. The pits are potential fugitive tank emissions sources, because stack risers or valve stems may extend from the tank through the concrete pits and blocks. The single-shell and double-shell tanks in each of the 200 Areas are listed in Table 1.1.



Figure 1.4. Photograph of the AP Tank Farm in the 200E Area (looking northeast)

Table 1.1. Single-Shell and Double-Shell Tank Farms at Hanford

200E Single-Shell Tank Farms	200E Double-Shell Tank Farms	200W Single-Shell Tank Farms	200W Double-Shell Tank Farms
A	AN	S	SY
AX	AP	SX	--
B	AW	T	--
BX	AY	TX	--
BY	AZ	TY	--
C	--	U	--

Chemical vapor emissions have been a concern at the tank farms despite efforts to understand vapor emissions. An increase in reported symptoms suspected to be related to chemical vapor exposures during early 2014 led to a focused revitalization of the chemical vapors hazard management program. Washington River Protection Solutions (WRPS) operates the Hanford tank farms for the U.S. Department of Energy (DOE), and has assembled a Hanford Tank Vapor Assessment Team (TVAT) to evaluate the

current WRPS program and to identify potential improvements. The *Hanford Tank Vapor Assessment Report* (Wilmarth et al. 2014) has compiled these assessments and made 10 overarching major recommendations and numerous supporting recommendations.

Several specific recommendations from the six Technical Assessment Areas described in the *Hanford Tank Vapor Assessment Report*, which are relevant to dispersion modeling, are as follows:

- Recommendation EA3: Use modeling, including computational fluid dynamics (CFD) methods, to determine the potential locations, conditions, and next steps in attempting to measure sporadic exposure events.
- Recommendation DR9: Develop a research strategy roadmap in partnership with DOE, National Laboratories, and university faculty subject matter experts to address critical questions regarding tank vapor emissions and exposures.
 - Action: Exploit capabilities within atmospheric chemistry and computational modeling to simulate vapor, gas, and aerosol dynamics that result in plume behavior. These model simulations should be capable of predicting transient plumes and would be of direct relevance for estimating worker exposures and informing dose-response studies.
- Recommendation RM7a: Establish a more effective methodology for designating vapor control zones (VCZs) and vapor reduction zones (VRZs).

In response to the TVAT recommendations, WRPS has published an implementation plan (WRPS 2015) describing specific actions that address its recommendations.

This report describes efforts by Pacific Northwest National Laboratory (PNNL) staff, through a project titled “Consolidation of Dispersion Modeling,” to support WRPS in addressing implementation plan actions and corresponding TVAT recommendations. This project includes a report that addresses three main tasks:

1. Overview of different types of dispersion models
2. Evaluation of specific models for four application areas
3. Review of a parametric dispersion study

The first task (summarized in Section 2.0 of this report) described the various types of dispersion models, including the dispersion methods, model inputs and outputs, and inherent model strengths and weaknesses. This task also identified candidate dispersion models that could be used for tank farm applications.

The second task evaluated the dispersion models presented in Section 2.0, and provided model and modeling recommendations for several specific tank farm applications. Section 3.0 presents these model recommendations, as well as recommendations to evaluate these models for specific use relative to tank-farm-specific geometries, meteorology, and applications. These two tasks provide fundamental information regarding general model categories and specific models to inform the appropriate application of specific models to address the WRPS implementation of the TVAT recommendations.

The third task in this project involved reviewing previous work that summarized ground-level and plume centerline concentrations for various tank farm stacks at discrete wind speed and atmospheric stability conditions (Droppo 2004). A review of the Droppo (2004) report, and a preliminary comparison with the latest U.S. Environmental Protection Agency (EPA) dispersion model (AMS/EPA Regulatory Model [AERMOD]) was performed to provide insight on potential differences in model results. These efforts are

presented in Section 4.0. Finally, Section 5.0 presents overall conclusions and summarizes recommendations for applying dispersion modeling for tank farm needs.

This report was first submitted in FY16 to address the topics described above. During FY17, this report was revised to add two models used for the tank farms, and relevant updates were also made to this text.

2.0 Atmospheric Dispersion Models

The Hanford tank farms have several potential sources of air emissions from actively and passively ventilated stacks, as well as fugitive emissions. Atmospheric dispersion models can be used to model vapor emissions from these sources in support of tank farm operations. Several application areas have been identified for which dispersion models could be used to support tank farm work activities, including

- real-time response (e.g., predicting plume locations and air concentrations during a release)
- worker safety and emergency planning (e.g., estimating air concentrations to protect workers by establishing safe distance VCZs and VRZs)
- regulatory compliance (e.g., estimating air concentrations at Hanford Site fence line locations, such as for the EPA)
- engineering and research applications (e.g., determining optimal stack heights or ventilation rates to minimize ground-level air concentrations).

Given the range of possible applications, different types of dispersion models are needed to accurately model the various temporal and spatial scales under consideration. Fundamentally, there are four types of dispersion models; in order of complexity, they are as follows:

- **Plume models:** Plume models are based on the assumption that a release from a continuous source has a concentration gradient described by Gaussian (normal) distributions in the vertical and horizontal directions. Meteorological conditions are assumed to be steady-state and horizontally homogeneous within each model time step, so the plume is transported in a straight line in the downwind direction from the release. Consequently, plume models have limited utility under certain conditions, such as during long-range transport (i.e., beyond 50 km), when the wind field may vary spatially, or during calm winds, when the winds may meander over time periods less than the model time step. Diffusion is usually approximated using horizontal and vertical dispersion coefficients, which are a function of atmospheric stability and downwind distance from the release.
- **Puff models:** Puff models simulate a release as a series of discrete puffs. Source characteristics, wind direction, wind speed, mixing depth, and atmospheric stability may change temporally and spatially. Terrain effects may be incorporated in the wind field. Puff dispersion coefficients may be time-based or Gaussian, using dispersion coefficients similar to a Gaussian plume model.
- **Particle models:** Particle models simulate a release by tracking a large number of particle trajectories. Each particle is followed over a fixed coordinate system and the concentration in each grid cell is found by summing the contribution from each particle. Particle models require the specification of a three-dimensional wind field. Terrain effects may be incorporated in the wind field.
- **Computational fluid dynamics models:** CFD models use numerical techniques to solve the differential equations describing material transport and diffusion on a computational grid. These methods use highly resolved model inputs and are generally used for relatively small spatial domains due to CFD's large computational cost.

Each of these model types uses the mean and turbulent wind components (either directly or parameterized) as the primary (and often exclusive) means of estimating gaseous contaminant concentrations. These are the dominant drivers of transport and diffusion in the atmosphere. Dispersion models also typically produce time-averaged results, which means that short-duration peak concentrations or intermittency of a plume cannot be gleaned through models. One exception is large-eddy simulations with CFD, which parameterize sub-grid-scale turbulence and produce output at high temporal resolution.

Other environmental conditions, such as pressure, temperature, and relative humidity, are not explicitly incorporated in many models.

Note that this model summary and evaluation effort is focused on dispersion models, and does not include discussions of models that include chemical reactions and does not explicitly address models that perform back-calculations from receptors. Photolysis (i.e., degradation of chemicals due to sunlight) or chemical conversions may occur in tank vapor plumes, but these processes are less important at small transport distances (e.g., less than tens of kilometers) and are therefore omitted here. Chemical processes that occur over time scales that are short relative to the transport time scale should be addressed in model analyses. Some models described within this report (e.g., CALPUFF, HYSPLIT) can incorporate simple atmospheric chemistry. In addition, the mechanism that triggers a release is not incorporated within these models. A user must prescribe both a release location and a release rate to drive the models described in this report. The definition of the source term is a particular challenge for the tank farms due to the uncertainties in chemical composition, concentration, and emission rates from both the double-shell and single-shell tanks. Previous studies have made limited measurements of the stack emissions, and additional measurements were made under the Vapor Monitoring and Detection System Pilot-Scale efforts at the AP Tank Farm, but dispersion modeling for the tank farms nonetheless requires that assumptions be made to prescribe the source inputs. Finally, the focus of this report is on dispersion models of chemical emissions; dispersion models that exclusively model radiological emissions have been omitted. The straight-line plume model, HotSpot, which is used in the WRPS emergency planning group and the Hanford Emergency Operations Center (EOC) for radiological emergencies, is excluded from this report for this reason.

Figure 2.1 illustrates some general differences among plumes produced from these four different types of models. As described above, plume models are based on a straight-line downwind transport from an emission point with simple meteorological input. Puff models allow the plume centerline to meander based on winds, which are often computed over a regular grid in the domain. Particle models achieve plume estimates through particle trajectories, which also rely on a gridded wind field. Finally, CFD models, which can use scalar or particulate dispersion, compute plumes based on a more detailed wind field that explicitly accounts for flow obstructions.

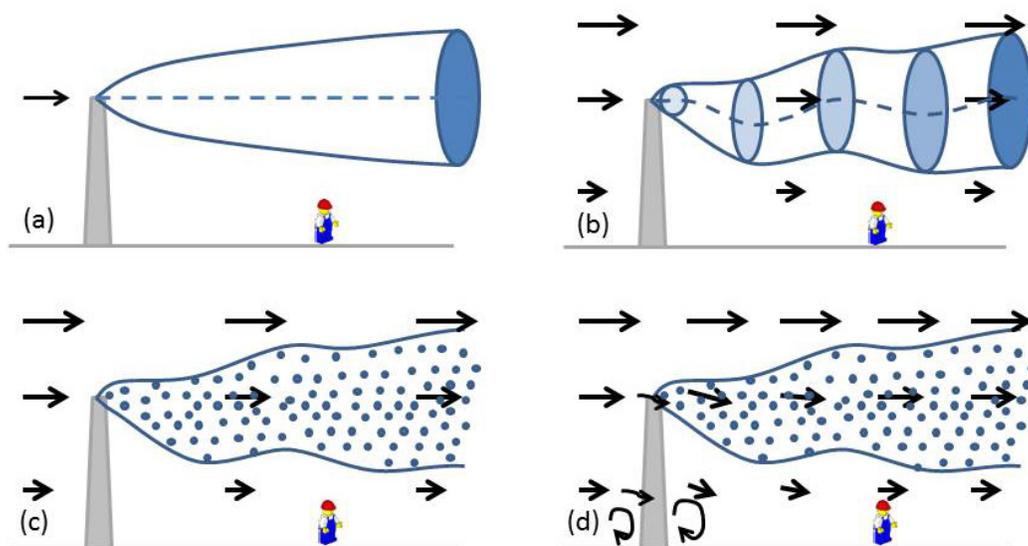


Figure 2.1. Plumes from an Elevated Release, Illustrating Differences between (a) Plume, (b) Puff, (c) Particle, and (d) CFD Models

The following subsections describe each model type in more detail and present candidate models for tank farm applications. Each subsection ends with a summary of model attributes. In Section 3.0, a ranking method is used to score the attributes to identify the candidate models that are likely best for tank farm operations in the areas of real-time response, worker safety and planning, regulatory compliance, and engineering and research tank farm applications.

Figure 2.2 illustrates key model attributes that may not be obvious to readers unfamiliar with dispersion modeling. Figure 2.2a shows an elevated plume undergoing standard dispersion downwind of a stack. Figure 2.2b shows stack-tip downwash, whereby the plume is brought downward at the release point due to low pressure on the lee side of the stack, as well as building wake effects, which tend to enhance diffusion. Figure 2.2c shows the effect of thermally buoyant or momentum-driven exhausts, which increases the effective stack height. Figure 2.2d illustrates the effect of fumigation, whereby turbulent eddies quickly bring the plume toward the surface, as a shallow morning mixed layer intercepts an elevated plume as a result of surface heating. Because of the shallow mixing depth, fumigation can result in a rapid increase in ground-level concentrations. However, fumigation events tend to be brief (generally lasting half an hour), as the mixed layer depth continues to increase in response to further surface heating (Turner 1994). Figure 2.2e and Figure 2.2f show the effect of a plume with stable layers (i.e., inversion levels) above and below the stack. When the inversion is below the plume (Figure 2.2e), it limits the dispersion to the surface, which is known as plume *lofting*. When the inversion is above the plume (Figure 2.2f), it limits dispersion aloft, which is known as plume *fanning*. Fanning can cause high ground-level concentrations from surface releases or elevated releases affecting nearby terrain (Slade 1968). The tank farms contain a variety of source elevations, including tall actively-ventilated stacks, short passively-ventilated stacks, and ground-level emissions, as described in Section 1.0.

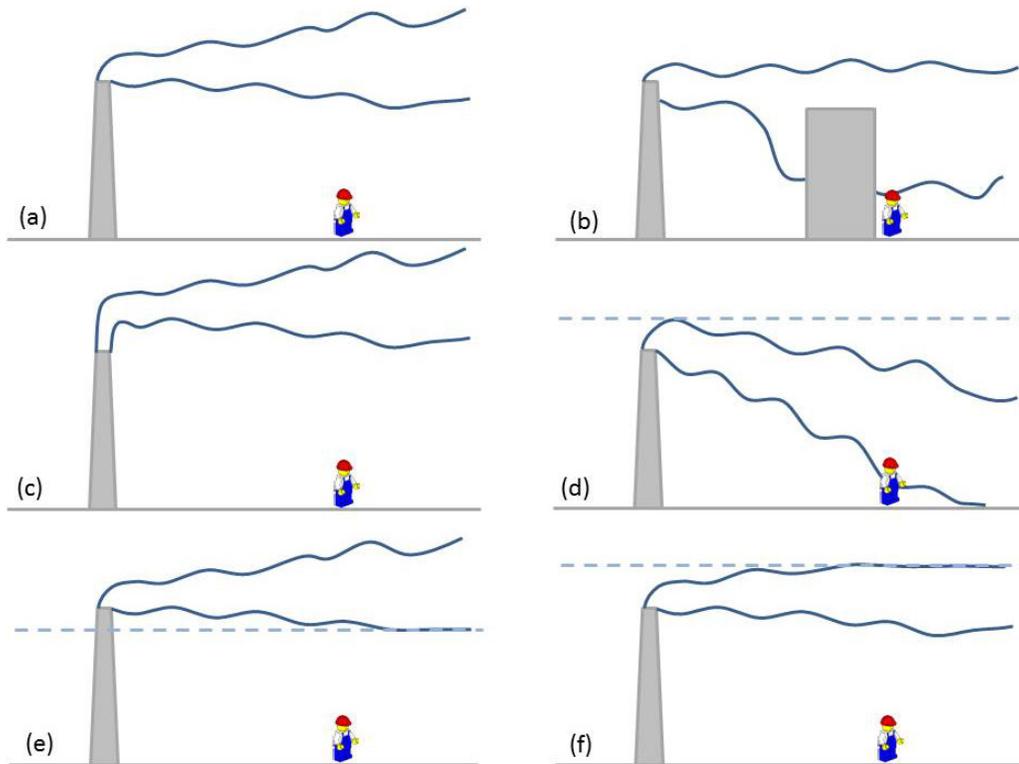


Figure 2.2. Illustration of Certain Attributes Considered in the Model Evaluation, including Modeling of (a) an Elevated Plume Release from a Stack, (b) Stack-Tip Downwash and Building Wakes, (c) Plume Rise from Momentum or Thermal Buoyancy, (d) Fumigation, (e) Plume Lofting, and (f) Plume Fanning

The objective of this section and the associated appendices is to describe the characteristics of the four basic model types to inform readers as to why a certain model may be preferred over another or to make model selections for specific applications. Model selection should be based on how well the model treats the most important attributes of the problem to be modeled; however, model selection is just one element of the modeling process. As noted above, model inputs can be challenging to define if appropriate data are not available. Model users should establish a process to document the assumptions and sources of model input data, the objective of the modeling exercise, and steps to evaluate the output of the model. These are important steps for any modeling project.

2.1 Plume Models

Plume models are one of the most basic dispersion models, and therefore tend to be the most widely used. Plume models estimate time-averaged concentrations at user-specified downwind distances; the concentration distributions are usually assumed to be Gaussian (i.e., a bell-shaped or normal distribution) both horizontally and vertically. Two conditions must apply to use a plume model: 1) the release must be continuous and 2) meteorological conditions must not vary with time or space (i.e., they must be homogeneous) during the release (Turner 1994) and within the model time step. These restrictions can limit the utility of plume models under certain conditions, such as instantaneous releases or when winds change temporally (e.g., plume meander) or spatially (e.g., long-range transport). However, the model simplicity allows plume models to run quickly, and many model codes incorporate modifications to the basic plume model to provide some flexibility in the conditions.

Several popular plume models were evaluated for use at the Hanford Site; these plume models are listed in Table 2.1 and are discussed further below. The models highlighted here are either commonly used in industry or are specifically known to be used at the tank farms. AERMOD (EPA 2004a) is the EPA preferred regulatory model, and is used at the Hanford tank farms to fulfill regulatory requirements as well as for a variety of exploratory analyses including stack height impacts. ISC (Industrial Source Complex [EPA 1995]) was the previous preferred regulatory model (superseded by AERMOD), and was used in the evaluation of peak to mean concentrations for the tank farms in Meacham et al. (2006). ARCON96 (Atmospheric Relative Concentrations in Building Wakes [NRC 1997]) is a U.S. Nuclear Regulatory Commission (NRC) regulatory model, which is not used at Hanford, but is included because it contains some specific modifications to treat low wind speeds, which occur approximately 25% of the time at the Hanford tank farms, based on nearby meteorological measurements (Hoitink et al 2005). EPIcode (Emergency Prediction Information code [DOE 2004]) is used for worker safety and emergency planning at the tank farms, and is part of the DOE Toolbox of quality-assured codes. ALOHA (Areal Locations of Hazardous Atmospheres [EPA 2007]) is a common model used in chemical releases. SAFER (SAFER Systems, LLC 2015) is a commercial data retrieval, data display, and modeling package evaluated for use at the tank farms as part of the pilot-scale testing activities. Finally, the American Industrial Hygiene Association (AIHA) Near- and Mid-Field Plume (hereafter referred to as AIHA-Plume) model (AIHA 2009) is a simple, center-line Gaussian plume model that incorporates two formulations for idealized near- (0 to 3 m) and mid- (3 to 100 m) field applications; it is used by the WRPS Industrial Hygiene group to evaluate releases within a tank farm. The AIHA-Plume model is part of a suite of models compiled by AIHA (IH-Mod) that WRPS uses for internal comparisons.

Table 2.1. Plume Models Evaluated for Use at the Hanford Tank Farms

Plume Model	Model Developer	Typical Application(s)
AERMOD ^(a)	EPA	Regulatory compliance; engineering and research applications
ISC	EPA	Regulatory compliance; engineering and research applications
EPIcode ^(b)	Homann Associates, Inc., LLNL/NARAC ^(d)	Real-time response; worker safety and emergency planning
ALOHA	NOAA/EPA	Real-time response; worker safety and emergency planning
ARCON96	NRC	Regulatory compliance; engineering and research applications
SAFER ^(b)	SAFER Systems, LLC	Real-time response; worker safety and emergency planning
AIHA-Plume ^(c)	AIHA	Worker safety and emergency planning; engineering and research applications

(a) AERMOD is currently used for regulatory compliance and engineering and research applications at the Hanford tank farms.

(b) EPIcode is currently used for worker safety and emergency planning applications at the Hanford tank farms. SAFER was under evaluation for use at the Hanford tank farms.

(c) The AIHA Near- and Mid-Field plume models are currently being used in worker safety and emergency planning and engineering applications by the WRPS Industrial Hygiene group.

(d) EPIcode was originally developed by Homann Associates, Inc. The model was acquired by Lawrence Livermore National Laboratory (LLNL) / National Atmospheric Release Advisory Center (NARAC) in 2012.

NOAA = National Oceanic and Atmospheric Administration

2.1.1 Dispersion Methods

Traditional plume models (e.g., ISC, EPIcode, ALOHA, ARCON96, SAFER) use “dispersion parameters” to account for turbulent diffusion. The dispersion parameters are a function of downwind distance and atmospheric stability, and provide an estimate of the plume spread due to turbulence. Several dispersion parameterizations exist, such as Pasquill-Gifford (PG) (Pasquill 1961) and Briggs (1974). These methods define discrete atmospheric stability classes that range from extremely unstable (stability class “A”) to extremely stable (stability class “F”). The horizontal and vertical dispersion parameters are then defined as a function of downwind distance for each stability class. The dispersion parameters can be adjusted to account for certain conditions, such as building wake (e.g., ISC, AERMOD, ARCON96) or low wind speed meander (e.g., AERMOD and ARCON96).

Contemporary dispersion models, such as EPA’s AERMOD, use direct measurements or estimates of horizontal and vertical turbulence, along with boundary layer similarity relationships, to calculate averaged atmospheric dispersion as a function of release height. The AIHA-Plume model formulations use a single, average dispersion coefficient based on PG stability class “C” (slightly unstable) to represent both horizontal and vertical diffusion at near (0 to 3 m) and mid (3 to 100 m) distances. As such, there is no mechanism to account for other or more conservative (e.g., highly stable) stability classes. Although the AIHA documentation cites “near” and “mid” field formulations, this distinction is somewhat arbitrary and misleading because the formulations are based on the PG parameterization where no such distinction is made (i.e., distances less than 100 m). Review of the AIHA mid-field (3 to 100 m) formulation indicates that it incorrectly uses the diffusion exponent from the far-field (greater than 100 m) formulation in the cited literature (Lipton and Lynch 1994). The mid-field concentrations are lower than the result

using the correct equation from the literature. Concentrations are about 2% lower at 3 m, and about 36% lower at 100 m.

2.1.2 Source Types

Plume models generally assume a release is from a point source, such as a stack. However, some plume models (e.g., ISC, AERMOD, EPIcode) have algorithms for modeling releases from other source types, including volume, area, and line sources; they include methods to account for the initial source size and release geometry. These models also account for changes in plume release height due to momentum and buoyancy effects, and for stack-tip downwash. In addition, some plume models (i.e., ISC and AERMOD) include release height adjustments from building wakes. The AIHA-Plume model assumes a point source release; there is no mechanism to account for plume rise, source size and geometry, or initial dispersion effects.

2.1.3 Meteorological Inputs

Plume models often require an hourly average estimate of wind speed, wind direction, and atmospheric stability to estimate hourly downwind plume concentrations. ALOHA requires hourly values, whereas SAFER is structured to accept 5-minute data. Regulatory plume models such as ISC and AERMOD have meteorological preprocessors (PCRAMMET [EPA 1999] and AERMET [EPA 2004b], respectively) that must be run in advance to generate model-ready input meteorological data files. The meteorological preprocessors require a year or more of historical hourly observations. ARCON96 also requires a year of formatted historical hourly observations, but has no meteorological preprocessor. The AIHA-Plume model only requires a single user-entered wind speed as an input; stability class is fixed and based on slightly unstable (i.e., PG “C”) atmospheric conditions.

2.1.4 Model Outputs

Plume models provide *time-averaged* air concentrations. For example, the PG dispersion coefficients are based on experimental tracer data that represent roughly a 10-minute average (Turner 1994). As long as meteorological conditions remain steady-state, the 10-minute average can be used to estimate longer-term averages. For example, ISC conservatively assumes the PG dispersion coefficients represent hourly averages. The model-predicted hourly averages are then compared to ambient air-quality standards that are also hourly averages (or greater) for certain criteria pollutants. Methods have been developed to estimate peak concentrations from plume model time-averaged concentrations. Cases where shorter time intervals are important must carefully consider the differences between the average value provided by the model, the average value for a short duration, and the maximum value within that short duration.

2.1.5 Strengths and Weaknesses

Because of their conservative nature, simplicity, and ease of use, plume models have gained wide acceptance, particularly in regulatory applications. Many of the plume models considered in this evaluation (i.e., ISC, AERMOD, ARCON96) have been validated in several model-to-model and/or tracer studies (e.g., EPA 2003). Although the assumptions of straight-line Gaussian plume models are often not completely satisfied for many dispersion modeling cases, the results of these models may be used with consideration of their limitations, which include the following:

- Plume models assume a release is continuous and therefore cannot model instantaneous or variable releases (Turner 1994). Non-continuous releases may be modeled as continuous releases, although the

model results must be evaluated carefully. This approach may produce conservative concentrations in some cases.

- Plume models do not account for spatial variations in meteorological conditions. Therefore, plume models are not expected to be reliable when there is a lot of spatial variability in the wind field (e.g., long-range transport) (EPA 2012).
- Plume models, in general, do not estimate maximum instantaneous concentrations. Some studies (e.g., Turner 1994) have developed general relationships between time-averaged and peak concentrations. For elevated releases, these short-duration, high-concentration conditions occur during unstable atmospheric conditions, when portions of the plume can be transported quickly to the ground with little dispersion (Turner 1994). In this case, air concentrations at downwind distances on the order of several effective stack heights can be comparable to air concentrations at the release point.
- Most plume models cannot accurately estimate air concentrations during fumigation events. Fumigation occurs when elevated plumes released in a stable layer are mixed rapidly downward, as the layer becomes unstable because of surface heating. Fumigation events tend to be transient, lasting approximately a half-hour or less (Turner 1994).
- Most plume models cannot accurately estimate air concentrations during calm wind conditions (40 CFR Part 51, Appendix W). During calm winds, the wind meanders back and forth, leading to a larger “apparent” dispersion. The standard dispersion parameters do not account for the meandering component of dispersion (which may result in conservatively high concentrations, but with a smaller area of impact).

Table 2.2 summarizes the various plume models considered for Hanford tank farm applications. Appendix A provides an in-depth summary for each candidate plume model considered in this report. Section 3.0 presents a ranking method for evaluating the use of these plume models at the Hanford Site.

Table 2.2. Summary Table for Plume Models

		AERMOD	ISC	EPIcode	ALOHA	ARCON96	SAFER	AIHA-Plume
Release Ht.	Ground-Level Release	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Elevated Release	Yes	Yes	Yes	Yes	Yes	Yes	No
	Thermally Buoyant	Yes	Yes	Yes	Yes	No	Yes	No
	Momentum	Yes	Yes	Yes	No	No	Yes	No
Release Type(s)		Gas & Particle	Gas & Particle	Gas & Particle	Gas	Gas	Gas & Particle	Gas
Source Type(s)	Point	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Area	Yes	Yes	Yes	No	Yes	No	No
	Volume	Yes	Yes	No	Yes	No	No	No
	Line	Yes	Yes	Yes	No	No	No	No
	Multiple Sources	Yes	Yes	No	No	No	Yes	No
Met. Input	Time Varying	Yes (hourly)	Yes (hourly)	No (single hour)	No (single hour)	Yes (hourly)	Yes (5-min)	No (single hour)
	Spatially Varying	No (point/tower)	No (point)	No (point)	No (point)	No (point)	No	No (point)
	Preprocessor	Yes (AERMET)	Yes (PCRAMMET)	No (single value)	No (single value)	No (formatted file)	No	No (single value)
Diffusion Mechanism		Similarity Theory	Pasquill-Gifford (rural) Brigg (urban)	Pasquill-Gifford	Pasquill-Gifford	Pasquill-Gifford (modified for low wind speed and building wake)	Pasquill-Gifford	Pasquill Gifford stability class "C" (i.e., slightly unstable) only

Table 2.2 (cont.)

	AERMOD	ISC	EPIcode	ALOHA	ARCON96	SAFER	AIHA-Plume
Unique Conditions	Inversion Layer	Yes	Yes	Yes	Yes	No	No
	Fumigation	No	No	No	No	No	No
	Low Wind Speed	Yes	No	No	No	Yes	No
	Building Wake	Yes	Yes	No	No	Yes	No
	Stack-Tip Downwash	Yes	Yes	No	No	No	No
Terrain Capability	Complex	Complex	Simple	Simple	Simple	Simple	Simple
Receptor Types	Discrete, Cartesian, Polar	Discrete, Cartesian, Polar	Discrete	Polar	Discrete	Discrete	Discrete
Applicable Distance(s)	< 50 km	< 50km	0.1 < x <50 km	0.1 < x < 10 km	< 10 km	0.1 km < x < 10 km	0.0 < x < 0.1 km ^(a)
Output Type(s)	Text, Chart, Contour	Text, Chart, Contour	Text, Chart, Graph	Chart, Graph	Text	Text, Chart, Contour	Text, Chart
Minimum Time Resolution	1 hr	1 hr	10 min	1 min	1 hr	5 min	10 min
User Interface	No (EPA) Yes (Commercial)	No (EPA) Yes (Commercial)	Yes	Yes	No	Yes	Yes (Excel)
Computer Platform	Windows	Windows	Windows	Windows	Windows	Windows, Mac	Windows
Run Time	Setup	Minutes to Hours	Minutes to Hours	Minutes	Minutes	Minutes	Seconds to Minutes
	Execution	Minutes	Minutes	Minutes	Minutes	Seconds to Minutes	Seconds to Minutes

(a) The AIHA-Plume documentation presents this as the applicable distance range; results may not be reliable at these distances.

2.2 Puff Models

Puff models are another type of common atmospheric dispersion model. As the name implies, puff models simulate the release as a series of puffs, which are tracked on a temporally and spatially varying meteorological grid. Concentrations on the grid are determined by summing the individual contributions from each puff. Puff models are ideal for modeling short duration (e.g., instantaneous) or continuous releases. Puff and plume models will provide similar estimates of air concentration for a continuous release when the meteorological conditions are homogeneous and steady state and the diffusion method is the same.

Table 2.3 lists the puff models included in this evaluation. The CALPUFF (California Puff [Scire et al. 2000a]) dispersion model is an EPA-preferred regulatory model for assessing near-field (i.e., <50 km, from the regulatory standpoint) applications involving complex meteorology that cannot be adequately addressed using a plume model or far-field (i.e., >50 km) applications, where long-range transport of pollutants is of concern. SCIPUFF (Second-Order Closure Integrated Puff Model [Sykes et al. 1998]) is an EPA alternative model that can also be used in certain approved near- and far-field regulatory applications. APGEMS (Air Pollutant Graphical Environmental Modeling System [Glantz et al. 2002]) was developed at PNNL and is used at the Hanford EOC as a confirmatory model for real-time emergency response applications on the scale of the Hanford Site and surrounding communities (~50 km). It is included in the DOE Subcommittee on Consequence Assessment and Protective Actions (SCAPA) Consequence Assessment Modeling (CAM) Toolbox, which means it complies with published software quality assurance requirements. Finally, the AIHA “Eddy Diffusion with Advection following Pulse Release” (hereafter referred to as AIHA-Eddy) model (AIHA 2009) is a simple, single-puff release model that assumes time- and space-invariant meteorological conditions; it is used by the WRPS Industrial Hygiene group to evaluate releases within a tank farm. The AIHA-Eddy model is part of a suite of models compiled by AIHA, and other models within this suite (IH-MOD), including continuous release models, are used by WRPS for internal comparisons.

Table 2.3. Puff Models Evaluated for Use at the Hanford Tank Farms

Puff Model	Model Developer	Typical Application(s)
APGEMS ^(a)	PNNL	Real-time response; Worker safety and emergency planning; Engineering and research applications
AIHA-Eddy ^(b)	AIHA	Worker safety and emergency planning; Engineering and research applications
CALPUFF	Sigma Research Corporation	Real-time response; Worker safety and emergency planning; Regulatory compliance; Engineering and research applications
SCIPUFF	Sage Management	Real-time response; Regulatory compliance; Engineering and research applications

(a) APGEMS is currently being used in real-time emergency response at the Hanford EOC.

(b) AIHA-Eddy is currently being used in worker safety and emergency planning and engineering applications by the WRPS Industrial Hygiene group.

2.2.1 Dispersion Methods

Typical puff models use the wind (direction and speed) to transport a puff away from the release point. During transport, the puff diffuses as a result of atmospheric turbulence. Similar to a plume model, puff diffusion is generally assumed to be a Gaussian distribution in the horizontal and vertical directions. Unlike plume models, however, the horizontal diffusion is applied radially, rather than in only the cross-wind direction, to grow the puff as it is transported. The diffusion coefficients can be based on simple PG distributions, calculated from micro-meteorological theory, or based on direct measurements of turbulence. The AIHA-Eddy model uses a single turbulent eddy diffusion coefficient for the horizontal and vertical directions; since atmospheric turbulence is not radially symmetrical, this limits the model's use to applications within several meters (<10 m) of the release point.

2.2.2 Source Types

Puff models generally assume a release is from a point source, such as a stack. However, some puff models (e.g., CALPUFF and SCIPUFF) have algorithms for modeling releases from other source types, including volume, area, and line sources; they include methods to account for the initial source size and release geometry. These models also account for changes in plume release height due to momentum and buoyancy effects, or for stack-tip downwash. In addition, some puff models (i.e., CALPUFF) include release height adjustments from building wakes. APGEMS and the AIHA-Eddy models only simulate releases from a single point source.

2.2.3 Meteorological Inputs

Generally, puff models use a meteorological preprocessor to generate gridded fields of wind speed, wind direction, and atmospheric turbulence to perform puff dispersion. For example, CALPUFF has a meteorological preprocessor (CALMET [Scire et al. 2000b]) that must be used in advance to generate the necessary model-ready input meteorological data file. However, some puff models, such as APGEMS, generate the gridded meteorological fields at runtime. The AIHA-Eddy model only uses a single input of eddy diffusion and wind speed in its dispersion calculation. This model simulates a single puff; therefore, it should be used in applications near the release point (<10 m).

While a single observation point can be used to generate the gridded meteorological fields, the use of multiple observation points can improve estimates. Additionally, high-resolution meteorological instrumentation (e.g., sonic anemometers) can provide the detailed turbulence information necessary to calculate puff diffusion coefficients directly.

2.2.4 Model Outputs

Puff models generally estimate *time-averaged* air concentrations. Regulatory models, such as CALPUFF and SCIPUFF, estimate hourly air concentrations for a grid of receptors. Real-time emergency response models, such as APGEMS, can provide shorter (i.e., 15-minute) time-averaged concentrations. The AIHA-Eddy model provides a nearly instantaneous estimate of air concentration at a point; however, since the diffusion coefficient is a constant value that is based on an average, measured value, the concentration estimate is a smooth function of time and does not capture the random variability of a real release.

Puff model output is, at a minimum, a concentration at a receptor location at a fixed point in time. Multiple receptors can show the contaminant distribution in space and time. APGEMS, CALPUFF, and

SCIPUFF provide concentration tables and plume contour plots as standard outputs. The AIHA-Eddy model provides the concentration time series at a discrete receptor point.

2.2.5 Strengths and Weaknesses

Unlike plume models, puff models can simulate instantaneous and short-duration releases, as may be likely from PBFs. In addition, most puff models can account for temporally and spatially varying meteorological conditions. As a result, puff models tend to perform well in situations where plume models do not, such as long-range transport, complex meteorology, or calm (meandering) winds (40 CFR Part 51, Appendix W). However, this benefit can be offset by increased runtimes, since the model has to create gridded meteorological fields and track individual puffs on the model grid. Other weaknesses include the following:

- Puff models require the use of many puffs to adequately resolve a continuous plume near a source, since the puffs are small and the separation distances can be great. Faster wind speeds increase the separation distance and can magnify the problem. Therefore, puff models may provide unsatisfactory results within a certain distance of continuous sources, until the puffs have grown large enough to be adequately resolved on the grid.
- Puff models tend to be more data intensive because they use meteorological observations from multiple stations to create the gridded meteorological fields. These models can therefore be more complicated to use because the meteorological data requirements result in more model inputs and settings than plume models.

Table 2.4 summarizes the puff models considered for Hanford tank farm applications. Appendix B provides an in-depth summary for each candidate puff model considered in this report. Section 3.0 presents a ranking method for evaluating the use of these puff models at the Hanford Site.

Table 2.4. Summary Table for Puff Models

		APGEMS	AIHA-Eddy	CALPUFF	SCIPUFF
Release Ht.	Ground-Level Release	Yes	Yes	Yes	Yes
	Elevated Release	Yes	Yes	Yes	Yes
	Thermally Buoyant	Yes	No	Yes	Yes
	Momentum	Yes	No	Yes	Yes
Release Type(s)		Gas & Particle	Gas	Gas & Particle	Gas & Particle
Source Type(s)	Point	Yes	Yes	Yes	Yes
	Area	No	No	Yes	Yes
	Volume	No	No	Yes	Yes
	Line	No	No	Yes	Yes
	Multiple Sources	No	No	Yes	Yes
Met. Input	Time Varying	Yes	No	Yes	Yes
	Spatially Varying	Yes	No	Yes	Yes
	Preprocessor	Yes	No	Yes	Yes
Diffusion Mechanism		Puff Spreading	Eddy Diffusion	Puff Spreading	2nd Order Closure Turbulence Model
Unique Conditions	Inversion Layer	Yes	No	Yes	Yes
	Fumigation	Yes	No	No	Yes
	Low Wind Speed	No	Yes	No	Yes
	Building Wake	Yes	No	Yes	No
	Stack-Tip Downwash	No	No	Yes	No
Terrain Capability		Simple	None	Complex	Complex
Receptor Types		Discrete, Cartesian, Polar	Discrete	Discrete, Cartesian, Polar	Discrete, Cartesian
Applicable Distance(s)		>100 m	x <10 m	>100 m	>100 m
Output Type(s)		Text, Contours	Text, Chart	Text, Chart, Contours	Text, Chart, Contours
Minimum Time Resolution		15 min	1 min	1 hr	15 min
Computer Platform		Windows	Windows	Windows	Windows
Run Time	Setup	Minutes	Minutes	Minutes	Minutes
	Execution	Seconds	Seconds	Minutes	Minutes

2.3 Particle Models

Particle models are a less common type of dispersion model compared with plume and puff models. These models use a large number of particles released into a three-dimensional wind field to simulate gaseous dispersion. Individual particles are tracked by applying a displacement according to the mean wind speed and direction at the individual particle location, and a random displacement according to

estimates of atmospheric turbulence. The concentration is determined by summing the contribution of each particle to the total release mass. Particle models are typically most appropriate for estimating concentrations at small scales (tens to hundreds of meters), although some models are tuned for greater distances.

Three particle models—the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, the Atmospheric Data Assimilation and Parameterization Tool / Lagrangian Operation Dispersion Integrator (ADAPT/LODI), and the Quick Urban & Industrial Complex (QUIC) model—have been selected for evaluation (Table 2.5). Appendix C provides an in-depth summary for each candidate particle model considered in this report. These models are not currently being used at the tank farms, but are commonly used in the modeling community for real-time response as well as for engineering and research. HYSPLIT (Draxler 1999) is a model that is often used for long-range transport problems. ADAPT/LODI (Leone et al. 2001) is a model that is supported by DOE for fast-response needs. QUIC (Nelson and Brown 2013) is a unique model that treats buildings and other flow obstructions with a relatively fast runtime.

Table 2.5. Particle Models Evaluated for Use at the Hanford Tank Farms

Particle Model	Model Developer	Typical Application(s)
HYSPLIT	NOAA	Real-time response; Worker safety and emergency planning; Engineering and research applications
ADAPT/LODI	LLNL	Real-time response; Worker safety and emergency planning; Engineering and research applications
QUIC	LANL	Real-time response; Worker safety and emergency planning; Engineering and research applications

LLNL = Lawrence Livermore National Laboratory; LANL = Los Alamos National Laboratory

2.3.1 Dispersion Methods

Dispersion in particle models is performed by first releasing a large number of particles into a gridded three-dimensional wind field. The total number of particles represents the total mass of contaminant released. The number of particles must be large enough to obtain a statistically sound concentration result. In general, these models can treat either instantaneous or continuous releases. The particles are displaced from the source according to the mean wind speed and direction plus a random speed according to the turbulence. Typically, vertical and horizontal turbulence are treated separately, and the turbulence is computed from the meteorological data (e.g., heat flux, temperature profile, or variability of the wind). Because a gridded wind field is used, the turbulence is calculated at each grid point, rather than using a single value for the entire domain.

2.3.2 Source Types

In general, particle models can release material from a variety of source types, from point, to area, line, or volume. Although HYSPLIT can only use single point or area releases, ADAPT/LODI and QUIC can accommodate both point and area releases as well as line and volume releases. ADAPT/LODI does not account for multiple releases in one simulation, but QUIC allows multiple release points. Both

ADPAT/LODI and QUIC address momentum and buoyancy effects at the source, but HYSPLIT does not treat momentum at the release.

2.3.3 Meteorological Inputs

HYSPLIT and ADAPT/LODI use real-time meteorological data as well as forecasts to support emergency response. HYSPLIT obtains both meteorological observations and forecasts from NOAA as well as a number of international meteorological networks and forecast groups. ADAPT/LODI obtains meteorological observations from NOAA weather stations, Air Force Weather Agency, and other military and DOE networks, including the Hanford Meteorological Network. QUIC is not currently configured to use real-time meteorological data. However, a variety of meteorological data input options are available, including single or multiple point values, single or multiple profiles, or gridded modeled wind fields. Basic data can be input relatively quickly for real-time response needs.

2.3.4 Model Outputs

Generally, particle models output concentration values or plots as a function of time. All the particle models evaluated here can report concentrations at selected receptors, and produce contour plots that show the plume coverage and plume arrival time. While HYSPLIT and ADAPT/LODI have online modeling platforms that allow users to select pre-populated output options, QUIC has some options within its graphical user interface (GUI) as well as the ready ability to output data for visualization in external software, such as Tecplot.¹

2.3.5 Strengths and Weaknesses

Particle models tend to be less common in operational applications than plume models, or even puff models, but are relatively common in research applications. However, for certain applications, particle models can provide temporal and spatial resolution not possible with plume models and more refined concentration fields than puff models. Both HYSPLIT and ADAPT/LODI are operated through a web interface, which allows the meteorological data input to be pre-defined for these models. HYSPLIT can also be downloaded and run on a local machine. ADAPT/LODI is operated through a reach-back capability through the National Atmospheric Release Advisory Center (NARAC). Some model-specific strengths and weaknesses are described below.

- HYSPLIT
 - Online model runs are convenient for users to operate, and the model is fast-running.
 - Back trajectory capability identifies likely source regions.
 - Not for applications at the tank farm scale.
- ADAPT/LODI
 - Online model runs through user login and has NARAC support.
 - Contains integrated databases for source terms and for meteorological data.
 - Included in the SCAPA CAM Toolbox, which means it complies with published software quality assurance requirements.
 - Not for applications at the tank farm scale.

¹ Bellevue, WA 98015

- QUIC
 - For applications where building awareness is needed.
 - Fast-running model with nearly the level of detail available from CFD.
 - Not for very large domains (tens of kilometers or more).

Table 2.6 summarizes the particle models considered for Hanford tank farm applications. Appendix C provides more in-depth summaries for each candidate particle model considered in this report. Section 3.0 presents a ranking method for evaluating the use of these particle models at the Hanford Site.

Table 2.6. Summary Table for Particle Models

		HYSPLIT	ADAPT/LODI	QUIC
Release Ht.	Ground-Level Release	Yes	Yes	Yes
	Elevated Release	Yes	Yes	Yes
	Thermally Buoyant	Yes	Yes	Yes
	Momentum	No	Yes	Yes
Release Type(s)		Gas & Particle	Gas & Particle	Gas & Particle
Source Type(s)	Point	Yes	Yes	Yes
	Area	Yes	Yes	Yes
	Volume	No	Yes	Yes
	Line	No	Yes	Yes
	Multiple Sources	No	No	Yes
Met. Input	Time Varying	Yes	Yes	Yes
	Spatially Varying	Yes	Yes	Yes
	Preprocessor	Yes	Yes	Yes
Diffusion Mechanism		Particle Dispersion and Puff Splitting	Particle Dispersion	Lagrangian Particle Dispersion
Unique Conditions	Inversion Layer	Yes	No	Yes
	Fumigation	No	No	Yes
	Low Wind Speed	No	No	Yes
	Building Wake	No	No	Yes
	Stack-Tip Downwash	No	No	Yes
Terrain Capability		Simple	Complex	Complex
Receptor Types		Discrete, Cartesian, Polar	Discrete, Cartesian, Polar	Discrete, Cartesian, Polar
Applicable Distance(s)		>100 m	>100 m	>10 m
Output Type(s)		Text, Chart	Text, Chart, Contours	Text, Chart, Contours
Minimum Time Resolution		1 hr	15 min	5 min
Ease of Use		Easy	Easy	Easy
Computer Platform		Windows, Mac, Linux, Online	Online only	Windows
Run Time	Setup	Minutes	Minutes	Minutes
	Execution	Minutes	Minutes	Minutes

2.4 Computational Fluid Dynamics Models

CFD models simulate fluid dynamics, mass transport, and energy exchanges by numerically solving three-dimensional transient mass, momentum, and energy conservation equations. CFD models can accommodate most terrain, source, and environmental conditions. However, because CFD models were designed to solve general fluid dynamics problems, they may lack the imbedded material databases and

tuned parameters for atmospheric dispersion applications. CFD models in particular require qualified users with suitable fluid dynamics and meteorology backgrounds to apply the model correctly and interpret the results appropriately.

CFD software is available as commercial software and open source code. The work reported here compares three commercial software products (Fluent, CFX, STAR-CCM+) and two open source codes (Multiphase Flow with Interphase Exchange [MFiX] and Fire Dynamics Simulator [FDS]). These models are listed in Table 2.7. CFX (ANSYS, Inc. 2016) was selected because the tank farms used this code through an AREVA contract to compare the effect of varying stack heights with AERMOD. Fluent (ANSYS, Inc. 2015) is a similar code, and like CFX is owned and distributed by ANSYS. It is commonly used in industry and academia. STAR-CCM+ (CD-adapco 2016) is a product of Siemens PLM Software that PNNL uses for a variety of applications, including for Hanford projects. MFiX (NETL 2016) was included as an example of a DOE-developed code. However, MFiX is not a model that was designed for atmospheric dispersion applications, and is expected to be inefficient in these applications. FDS (NIST 2017) is a code developed by the National Institute of Standards and Technology (NIST) under the Department of Commerce and is currently being used by the tank farms through a contract with Kenexis. FDS was developed for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires; it provides features to simplify and accelerate the simulation setup for the application of atmospheric dispersion. Note that a software package called COMSOL Multiphysics is also used by WRPS engineers; however, it was not specifically evaluated here because the CFD module for this software package has not been used by WRPS for atmospheric dispersion studies. COMSOL has been used to investigate heat transfer in tanks, and the CFD component is expected to be similar to other commercial CFD codes. Detailed comparisons are listed in Table 2.8, and detailed explanations and technically based comparisons are provided in Appendix D. Note that the tables only compare features relevant to the simulation of tank farm vapor releases.

Table 2.7. Computational Fluid Dynamics Models Evaluated for Use at the Hanford Tank Farms

CFD Model	Model Developer	Typical Application(s)
Fluent	ANSYS	Worker safety and emergency planning; Engineering and research applications
CFX ^(a)	ANSYS	Worker safety and emergency planning; Engineering and research applications
STAR-CCM+	CD-adapco	Worker safety and emergency planning; Engineering and research applications
MFiX	NETL	Worker safety and emergency planning; Engineering and research applications
FDS ^(b)	NIST	Worker safety and emergency planning; Engineering and research applications

(a) CFX is used by AREVA for Hanford Tank Farms engineering and research applications.

(b) FDS is used by Kenexis for Hanford Tank Farms engineering and research applications.

NETL = National Energy Technology Laboratory

2.4.1 Dispersion Methods

CFD models may compute dispersion using either continuum or discrete particle schemes. For the continuum scheme, which is more widely used for dispersion problems, the gaseous or particulate concentration is modeled as a scalar field, and solved by the convection diffusion equation. For turbulent flow, the effective diffusivity is modeled as the summation of the molecular diffusivity and eddy diffusivity. The eddy diffusivity is usually a function of turbulent viscosity. For the discrete particle scheme, a gas or particle release is modeled by particles, and the particles move along the streamlines by a numerical trajectory calculation method. Fluctuations are added in the trajectory calculation to mimic the molecular and eddy diffusion effects. This is similar to, but more sophisticated than, the process described for particle models in Section 2.3. Note that whether the actual release is gaseous or particulate, both numerical schemes (continuum or discrete particle) can be used to simulate its atmospheric dispersion.

2.4.2 Source Types

For these and generally all CFD models, there are no limitations on the release type (point, line, surface, moving, or multiple releases). The model discretizes the domain to solve the equations of fluid motion, so a true point source does not exist; however, a small surface or volume may be used effectively as a point source. Additionally, the model can replicate specific release geometries explicitly (such as the exit plane of a stack), which is not generally possible with plume, puff, and some particle models.

2.4.3 Meteorological Inputs

CFD domains require boundary and initial conditions, which can be as simple as prescribing a velocity profile as both an inlet boundary condition and domain initial condition. The meteorological profile can be discrete data or a function. The meteorological profile can also be varied with time. In general, there is a high degree of flexibility and ability to customize meteorological input for CFD simulations. If meteorological data are only available from within the simulation domain, it can be used as a boundary condition itself, or a calibration run can be performed to iterate through varying velocity inlet boundary conditions to closely match the meteorological data at the measured location. It is impractical to use real-time meteorological data with CFD simulations because these models are not structured for such input, and the model runtime is significantly longer than the update rate of real-time meteorological data. Similarly, CFD models are well-suited for case studies, but not necessarily for investigations that use years of historical data as one might perform with AERMOD.

As mentioned above, (Section 2.4), FDS includes features that streamline atmospheric dispersion applications. For meteorological inputs, FDS employs a synthetic eddy method to “inject” eddies into the flow at random positions at the inlet boundaries to generate a more realistic wind field. FDS also allows data “nudging”—a data assimilation technique that adds a mean forcing term to the momentum equation to “nudge” the solution toward a desired wind field. Currently, FDS can only “nudge” the solution toward desired mean flow velocities; however, these mean flow velocities can be functions of time and/or height. Other CFD software packages that were not designed for atmospheric conditions (e.g., STAR-CCM+, CFX, Fluent) do not provide convenient methods for developing appropriate wind conditions, and require considerable development with user-defined functions to achieve comparable capabilities.

2.4.4 Model Outputs

The three commercial CFD software packages examined here store simulation results in their own formats, and results can be visualized in the software GUI. The results can also be exported to different formats for visualization in third-party tools, such as Tecplot,¹ VisIt,² and ParaView.³ Log data can also be exported during post-processing or simulation. Log data include convergence history and time series of velocity, concentration, and pressure at user-defined locations in the simulation domain. For the open source CFD model MFiX, the results can be stored in ParaView format for data visualization. (No visualization tools are available within MFiX itself.) Log data can be exported from ParaView or generated during the simulation. For the open source CFD model FDS, the results are stored in the model's own format, which can be visualized by Smokeview, an open source visualization program that was also developed by NIST. Alternatively, the FDS simulation results can be exported to a format used by the graphics package Plot3D. Although Plot3D is an old tool that is no longer supported, the data file can be opened by third-party tools such as Tecplot. FDS outputs not only the time varying results for the whole simulation domain, but also selected surface and iso-surfaces, points, lines, and statistical data.

2.4.5 Strengths and Weaknesses

In general, CFD's advantage over other modeling approaches is its flexibility in solving a variety of problems because fluid transport equations are solved within the model. CFD can model almost any dispersion case, and provide more detail (both in space and time) than plume or puff models. However, CFD models require a significant effort to set up and have a high computational cost. This makes case studies that investigate the details of the flow and dispersion the most appropriate application of this type of model, while investigations with numerous hours of simulation are generally not feasible. Similarly, very large computational domains become impractical, so domains should be limited to a few kilometers on a side. Although there is no theoretical solid domain size limit for CFD models, these models require a relatively small grid resolution to resolve the important flow dynamics from the effects of complex geometries (i.e., buildings, terrain) and the number of grid cells directly translates to computational cost. While a coarse mesh may reduce the computational cost of a simulation, significant increases in the grid size will reduce the detail in the results, which defeats the original intent of using CFD. CFD codes have been designed to solve general fluid dynamics problems, so manual setup of gas/particle databases, inclusion of flow-obstructing geometries, and specification of boundary conditions are needed. These model setup activities require a competent user to ensure that all elements are correctly defined.

The capabilities and advantages of the three commercial CFD packages as presented in Table 2.8 are identical. They each provide user-friendly, advanced geometry modeling and meshing tools, and a powerful post-processing and visualization tool. Commercial CFD software solvers are well-validated and robust, and their parallel computation efficiency is high. Most widely used turbulence models are available in these three commercial CFD codes. In addition, Fluent supports graphic processor unit (GPU) simulation acceleration. A single GPU contains from a few hundred to over 2000 computing cores, compared with central processing unit (CPU) cores, which only contain tens of cores. Although GPU cores are simplified compared with CPU cores, the addition of hundreds of cores with GPU allows for massive parallel computation, which generally increases simulation speed over traditional CPUs.

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² Lawrence Livermore National Laboratory, Livermore, CA 94550

³ Sandia Corporation, Kitware Inc., Albuquerque, NM 87185

One limitation of commercial CFD software is the cost of purchasing licenses, which often exceeds \$10,000 per user per year. In addition, although the commercial CFD packages allow users to define functions or code to achieve some desired functions, they are not always as flexible as open source code.

The advantages of the open source code MFiX are that it is free and allows users to modify the source code. However, MFiX lacks a mesh generator that can support unstructured adaptive mesh. This means that tank-farm-scale simulations would require significantly more grid cells compared with the commercial codes, which would substantially increase computational cost. MFiX's parallel computational efficiency is also lower than the three commercial CFD packages. In terms of ease of use, MFiX only provides a test version of the GUI, and no post-processing and visualization tools. Another consideration with open source code is that community modification of the code may not be a desired trait.

The open source code FDS is a unique CFD model that has been designed for atmospheric dispersion applications. A significant advantage of this code is the ease of model setup. Simple text files are used to define the problem, then, upon model execution, the code produces the necessary computational mesh. This approach makes FDS efficient, which allows large numbers of simulations to be set up with relative ease. Meshing tends to be fast and flexible; however, users must still exercise caution when adjusting parameters that may lead to significant changes to the mesh. Other models that use simple text file inputs require manual pre-processing of the computational mesh, and simulation stability and accuracy tends to be sensitive to the mesh quality. Commercial CFD models typically use code-specific file formats. FDS only supports a structured Cartesian mesh, which means that solid objects in the FDS simulation are approximated by cuboids, so it is inefficient for complex geometries. Tools such as Blender FDS or PyroSim are available to convert CAD geometries into the FDS input file. BlenderFDS is a free, open source, three-dimensional creation suite that also provides a GUI for FDS to set up simulations. PyroSim, which is a commercial software tool from Thunderhead Engineering Consultants, Inc., provides a more complete GUI for FDS, and helps the user quickly create and manage the details of complex FDS simulations.

The primary disadvantages of CFD codes are summarized below:

- High computational cost and long run-times
 - Limitations to the computational domain size
- High license costs for commercial codes
- Significant model set-up time
- Codes have typically not been explicitly developed for dispersion modeling, so model output must be carefully evaluated by a knowledgeable user

Table 2.8 summarizes the CFD models considered for Hanford tank farm applications. At their roots, all CFD models were designed to treat general fluid dynamics and related mass and energy transport problems, so each model can address all of the atmospheric dispersion applications listed in Table 2.8. However, the difference between CFD models and traditional dispersion models is that there may be significant challenges to set up the appropriate simulation parameters within the CFD model and to validate the results. Among the CFD models, the ability to establish the appropriate model setup may also vary based on the original intent and development strategy for each particular CFD model. Appendix D provides a summary of these models for CFD-specific attributes. Section 3.0 presents a ranking method for evaluating the use of CFD models at the Hanford Site.

Table 2.8. Summary Table for CFD Models

		Fluent	CFX	STAR-CCM+	MFiX	FDS
Release Ht.	Ground-Level Release	Yes	Yes	Yes	Yes	Yes
	Elevated Release	Yes	Yes	Yes	Yes	Yes
	Thermally Buoyant	Yes	Yes	Yes	Yes	Yes
	Momentum	Yes	Yes	Yes	Yes	Yes
Release Type(s)		Gas & Particle				
Source Type(s)	Point	Yes	Yes	Yes	Yes	Yes
	Area	Yes	Yes	Yes	Yes	Yes
	Volume	Yes	Yes	Yes	Yes	Yes
	Line	Yes	Yes	Yes	Yes	Yes
	Multiple Sources	Yes	Yes	Yes	Yes	Yes
Met. Input	Time Varying	Yes	Yes	Yes	Yes	Yes
	Spatially Varying	Yes	Yes	Yes	Yes	Yes
	Preprocessor	Yes	Yes	Yes	Yes	Yes
Diffusion Mechanism		Continuum scalar field diffusion convection, and particle tracking	Continuum scalar field diffusion convection, and particle tracking	Continuum scalar field diffusion convection, and particle tracking	Continuum scalar field diffusion convection, and particle tracking	Continuum scalar field diffusion convection, and particle tracking
Unique Conditions	Inversion Layer	Yes	Yes	Yes	Yes	Yes
	Fumigation	Yes	Yes	Yes	Yes	Yes
	Low Wind Speed	Yes	Yes	Yes	Yes	Yes
	Building Wake	Yes	Yes	Yes	Yes	Yes
	Stack-Tip Downwash	Yes	Yes	Yes	Yes	Yes
Terrain Capability		Complex	Complex	Complex	Simple	Complex
Receptor Types		Discrete, Cartesian, Polar				
Applicable Distance(s)		<5,000 m				
Output Type(s)		Text, Chart, Contours	Text, Chart, Contours	Text, Chart, Contours	Text, Chart	Text, Chart, Contours
Minimum Time Resolution		Seconds	Seconds	Seconds	Seconds	Seconds
Computer Platform		Windows, Linux	Windows, Linux	Windows, Linux	Windows, Linux	Windows, Linux, MacOS
Run Time	Setup	Hours	Hours	Hours	Hours	Hours
	Execution	Hours-days	Hours-days	Hours-days	Hours-days	Hours-days

3.0 Application-Specific Model Evaluations

Section 2.0 described four different types of dispersion models (plume, puff, particle, and CFD) that could potentially be used to model vapor releases from the Hanford tank farms. Within each type, candidate dispersion models were identified. The models were binned into the four application areas introduced in Section 2.0—real-time response, emergency planning, regulatory compliance, and engineering and research applications—depending on the model’s intended purpose and historical use. This section evaluates each of the models in the four application areas to inform the suitability of each model for tank farm operations.

A ranking method was developed to perform the model evaluation. Specifically, model attributes were identified in the following areas:

- Release capability
- Meteorological capability
- Terrain capability
- Receptor types
- Applicable distance(s)
- Time averages
- Output products
- Usability
- Runtime

For each of the four application areas, a table was developed to weight the importance of each attribute. For example, a fast runtime is critically important for a real-time response dispersion model, but is far less important for a regulatory compliance dispersion model. The attribute weighting factors range from 0 to 2, and are defined in Table 3.1. Specific model attributes within these areas listed above were selected based on the importance of that attribute for one or more application areas or the possibility that an attribute may be important in the future. For example, wet and dry deposition is included in the meteorological capability category, but it is always assigned a weighting factor of 0 because deposition is not considered important for gaseous vapors concerns. However, the formation of aerosols is a current topic under consideration; these attributes were included to easily allow updates to the model ranking.

Table 3.1. Attribute Weighting Factors Used in the Evaluations

Weighting Factor	Definition
0	Attribute is not important to application area.
1	Attribute has low importance to application area.
2	Attribute has high importance to application area.

Each dispersion model considered in a given application area was then assigned a score based on how well it accounts for each attribute. Model scores range from 0 to 2, and are defined in Table 3.2.

Table 3.2. Model Scores Used in the Evaluations

Model Score	Definition
0	Model does not address the attribute.
1	Model addresses the attribute.
2	Model addresses the attribute particularly well.

For each application area, the attribute weighting factor (Table 3.1) was multiplied by the corresponding model score (Table 3.2) to determine a weighted-model score for that attribute. The weighted-model scores were then summed across all attributes to determine the overall model score. The dispersion model with the highest overall score is considered the best model in that application area for supporting Hanford tank farm operations. Note that the contribution of each attribute is essentially equal among attributes, so a high score alone does not define the best model for an application. The model must be scrutinized to ensure that any critical attributes are also addressed by the model.

In some cases, a dispersion model may have been considered in more than one application area. For example, AERMOD could potentially be used in regulatory compliance and engineering/research applications. In this case, separate model scores were developed specific to each application area. Consequently, the model's overall score will be different in each application area.

The following subsections present the model evaluation results for each application area. Since several dispersion models were considered in each application area, only the attribute weights and overall scores are presented. Appendix E through Appendix H contain the individual model scores in each application area that were used to determine the overall scores.

3.1 Evaluation of Real-Time Response Models

Real-time response modeling may be triggered by a worker exposure report or an elevated sensor measurement. The purpose of real-time modeling is to identify the current plume location and concentrations to evaluate worker exposure levels, direct workers away from a plume, and direct response workers toward safe pathways. A real-time response model may also be run nearly continuously to provide dispersion results as updated source or meteorology data become available. This type of model operation can enable users to decide whether to 1) start or stop work within the farm, 2) move staff out of facilities adjacent to the farm, and/or 3) require staff to use personal protective equipment. A real-time model needs to run quickly, provide output at relatively high temporal frequency, account for real-time (time-varying) meteorology, have good spatial resolution, and provide output that is easy to use, implement, and understand.

Table 3.3 lists the attributes and corresponding weighting factors that were assigned in the real-time model evaluation. Attributes with a weighting factor of 2 are considered highly important for real-time modeling applications at the Hanford tank farms. The following considerations were used in developing the weighting factors:

- **Release Capability:** The Hanford tank farms have both passive, ground-level and (elevated) actively-ventilated stack releases. These releases could have higher effective release heights due to thermal buoyancy or vertical momentum, but these effects are not expected to significantly influence concentration estimates. The releases are assumed to be in a gas (vapor) phase, not particulate. Sources are most likely modeled as point sources, with area or volume sources as possibilities of

lower importance, and line sources of least importance. Finally, multiple sources might need to be modeled across multiple tank farms, or possibly non-tank-farm sources that may affect tank farm space, but this is of lesser importance because it is unlikely that multiple releases would combine to concentrations of significance.

- **Meteorological Capability:** Real-time dispersion models should use real-time meteorology, varying with time as an event proceeds. The meteorological data do not necessarily need spatial variability due to the typical small-scale dispersion considered in real-time events. Historical meteorological data capability is not particularly important for this application, but may be useful in certain cases. The dispersion model should consider the inversion layer as a reflective boundary condition and account for fumigation. However, low wind speeds, building wakes, and stack-tip downwash are the most important unique meteorological conditions, since these have the largest impact at the spatial scales within a tank farm. Deposition is not considered important for estimating tank farm vapor air concentrations.
- **Terrain Capability:** The effect of uneven terrain is important because there are elevation differences between the tank farm and the surrounding area, which makes receptor elevation important. Terrain steering effects at the spatial scales of interest are of lesser importance.
- **Receptor Types:** Real-time dispersion models should allow for discrete receptors to calculate air concentrations at specific locations. Since the domain for real-time responses tends to be small, a Cartesian grid or polar grid is not as important.
- **Applicable Distance(s):** Since a single tank farm is typically on the order of 100×200 m, the most important distance is less than 100 m from a source or suspected source. Distances beyond 100 m, which represent distances between tank farms, up to the length scale of the Hanford Site, are also relatively important. For real-time applications, long-range transport in excess of 15 km is not considered important.
- **Outputs:** Text files are the standard way of outputting air concentrations for receptors; usually the output is in the form of tables of highest air concentrations at each receptor location. Contour plots can be used to quickly visualize the tabular data. Ground deposition computation or output is not important for real-time response for vapors concerns.
- **Time Averages:** For a real-time response to the Hanford tank farm vapor concerns, sub-minute concentrations are of highest importance, but concentrations at time averages of 15 minutes (or longer) are also important for consequence analyses.
- **Usability:** Real-time dispersion models should be easy to use, with an intuitive user interface to limit confusion or errors during an event. Models should also be validated, with accuracy information that is understood by the user.
- **Runtime:** Both fast setup and fast execution are particularly important for real-time modeling.

Table 3.3. Real-Time Model Attribute Scores

Attributes	Weight (0-2)	Attributes	Weight (0-2)
Release Capability		Receptor Types	
Ground-Level Release	2	Discrete	2
Elevated Release	2	Cartesian Grid	1
Thermally Buoyant	1	Polar Grid	1
Momentum	1	Applicable Distance(s)	
Gas	2	≤100 m of release	2
Particles	0	100 m to 15,000 m	1
Point	2	15,000 m to 50,000 m	0
Area	1	≥50,000 m	0
Volume	1	Outputs	
Line	0	Air Concentration	2
Models Multiple Sources	1	Ground Deposition	0
Meteorological Capability		Text	2
Time Varying	1	Chart	1
Spatially Varying	1	Contour Plots	1
Real-Time Meteorology	2	Time Averages	
Historical Meteorology	1	≤1 minute	2
Inversion Layer	1	>1 minute	1
Fumigation	1	Usability	
Low Wind Speed	2	User Interface	2
Building Wake	2	Ease of Use	2
Stack-Tip Downwash	2	Validation/Accuracy	2
Dry Deposition	0	Runtime	
Wet Deposition	0	Fast Setup	2
Terrain Capability		Fast Execution	2
Uneven Terrain	2		
Terrain Steering	1		

Table 3.4 summarizes the scores for the models selected for real-time modeling. Details of the model scores are included in Appendix E. These models were selected because they offer fast setup and runtimes, are currently used in emergency response by government agencies or industry, and are appropriate for the primary spatial scales of interest (up to several hundred meters). CALPUFF, as delivered by the EPA, is not a model with fast setup times; however, the time-consuming steps of running the CALPUFF preprocessors have been automated in at least one example application (Rishel and Glantz 2008), so it has been included here as a possible emergency response model. Based on these scores, the top three models are CALPUFF, APGEMS, and QUIC. These models are different from one another, with specific attributes to consider when approaching specific real-time response needs. For example, APGEMS, unlike CALPUFF or QUIC, does not treat volume, line, or multiple sources. However,

APGEMS currently accepts real-time meteorology from the Hanford Meteorological Network. Both APGEMS and CALPUFF are puff models, so they are generally applied at distances in excess of 100 m. The QUIC model, on the other hand, is a particle model that explicitly accounts for flow obstructions. QUIC has been designed to provide plume concentrations in urban environments at the temporal and spatial resolution of CFD, without the computational cost of a CFD model. QUIC runs quickly, and is easy to use and implement.

Table 3.4. Real-Time Model Scores.

Model	Total Score ^(a)	Model Type	Comments
CALPUFF	70	Puff	Not intended for sub-kilometer distances
APGEMS	66	Puff	Closest source to receptor distance – 100 m. Operates with real-time data from the Hanford meteorological network.
QUIC	66	Particle	Explicitly accounts for flow obstructions (e.g., buildings). Real-time meteorology development needed.
ADAPT/LODI	60	Particle	DOE-supported fast-response model
HYSPLIT	60	Particle	Not intended for sub-kilometer distances
EPIcode	50	Plume	Part of DOE Toolbox, in use at tank farms, but not for real-time response
ALOHA	49	Plume	Common for chemical releases
SAFER	44	Plume	Single source capability, under evaluation as part of pilot-scale testing at tank farms

(a) Maximum possible score (all attributes received a value of 2) is 110.

The only real-time model that is currently used at the Hanford tank farms is EPIcode. This model is used in the emergency planning group to evaluate chemical hazards to identify conservative concentrations from worst-case emissions sources. Predicted distances to Protective Action Criteria (PAC) levels are reported to provide emergency responders with estimates needed to make rapid decisions about response strategies (e.g., evacuate versus shelter). WRPS does not use EPIcode as a real-time response model; the Hanford EOC performs real-time modeling.

Both EPIcode and ALOHA are commonly used in emergency planning and response, despite their relatively low ranking on this list. As plume models, these models are simple to set up and to execute, so they excel in the areas of usability and runtime, which is the primary driver for implementing these models for emergencies. EPIcode and ALOHA are limited in the areas of meteorological and terrain capabilities, which are treated particularly well by puff and particle models.

SAFER was under evaluation during pilot testing, but the recommendation from the testing was to discontinue further use of this software. SAFER is a basic plume model that uses real-time gaseous sensor and meteorological measurements. The strength of the SAFER model is the ability to use these measurements to define the source strength; however, there are errors in the source strength and source position defined by SAFER for tank farms release rates, which contributed to the recommendation to discontinue use of this software.

While it seems less obvious to use CFD for real-time applications due to the extensive computation effort required, it could be made feasible by running model simulations in advance for typical or anticipated problematic meteorological conditions. The basic steps required are to 1) examine historical met conditions, 2) develop models for selected cases, and 3) run simulations for and save flow fields for use.

Note that these would be steady-state simulations for a limited set of cases. Expected source locations could be pre-configured in the model and represented as trace scalars and selected to compare with detected releases. These stored cases would be available with no or little required computation, but would be limited to the library that had been developed. How well this real-time application would work and the limits of its utility would be determined through assessments as outlined under the research application below. Confidence in the real-time application needs to be built on model evaluation under a variety of conditions. Using the models for conditions not included in this evaluation could give misleading results.

3.2 Evaluation of Worker Safety and Emergency Planning Models

Worker safety and emergency planning, unlike the real-time modeling application, does not require a quick turnaround product. There is generally no trigger event for this type of modeling; instead, this may be a planning tool to establish worker evacuation strategies in the event of high concentration detection, establishing the concentrations and likelihood of such events, and establishing worker protection for routine bases. Evaluating likely or extreme concentrations at tank farm fence lines and establishing VCZs and VRZs are included under this model application. This type of application particularly benefits from models that include a broad range of meteorological conditions to ensure that the model output allows users to make well-informed decisions. Lookup tables that reveal site-specific meteorological conditions most prone to high vapor concentrations at workplace locations (either inside or outside a given farm) are also useful tools under this application.

Other phenomena that are important, but are not generally incorporated into models, are transient conditions, including fumigation and short-duration (from seconds to minutes) peak concentrations. Most models predict average concentrations, which are appropriate when evaluating long-term worker exposures; however, peak concentrations are the primary concern in the tank farm bolus exposures. Peak concentrations can exceed average concentrations by an order of magnitude, so all model output should be understood with this limitation in mind. Additionally, modeling average concentrations often assumes steady-state release rates, which may occur from double-shell tanks due to the active ventilation systems. However, that is likely not the case for passively ventilated single-shell tanks.

Table 3.5 lists the attributes and corresponding weighting factors that were assigned in the emergency planning model evaluation. Attributes with a weighting factor of 2 are considered highly important for this application at the Hanford tank farms. The following considerations were used in assigning weighting factor values to the various attributes:

- **Release Capability:** The Hanford tank farms have both passive, ground-level and (elevated) actively-ventilated stack releases. These releases could have higher effective release heights due to thermal buoyancy or vertical momentum, but these effects are not expected to significantly influence concentration estimates. The releases are in a gas (vapor) phase, not particulate. Sources are most likely modeled as point sources, with area or volume sources as possibilities of lower importance, and line sources of least importance. Finally, multiple sources might need to be modeled across multiple tank farms, or possibly non-tank-farm sources that may affect tank farm space, but this is of lesser importance because it is unlikely that multiple releases would combine to concentrations of significance.

- **Meteorological Capability:** The development of emergency planning lookup tables or other worker safety and emergency planning tools would not use real-time meteorology. However, it would require the ability to use historical data to develop those cases suggestive of bounding dispersion conditions. The meteorological data do not necessarily need spatial variability or time variability due to the typical small-scale dispersion and single case study nature of this application. The dispersion model should consider the inversion layer as a reflective boundary condition and account for fumigation. However, the ability to correct for low wind speeds, building wakes, and stack-tip downwash are also very important as these have the largest impact at the spatial scales within a tank farm. Deposition is not considered important for estimating tank farm vapor air concentrations.
- **Terrain Capability:** The effect of uneven terrain is important because there are elevation differences between the tank farm and the surrounding area, which makes receptor elevation important. Terrain steering effects at the spatial scales of interest are not important.
- **Receptor Types:** Emergency planning lookup tables would be based on discrete receptors. The ability to provide results in Cartesian grid or polar grid is not as important.
- **Applicable Distance(s):** Since a single tank farm is typically on the order of 100×200 m, the most important distance is less than 100 m from a source or suspected source. Distances beyond 100 m, which represent distances between tank farms, up to the length scale of the Hanford Site, are also relatively important for onsite impacts. Long-range transport in excess of 1 km is not important, and distances greater than 15 km are expected to be unnecessary for this application. Very short distances (within about 20 m of the source) are important for the specific portion of this application that addresses VCZs and VRZs.
- **Outputs:** Text files are the standard way of outputting air concentrations for discrete receptors, and can be used for lookup tables as well as for developing both routine and event worker protection strategies. Charts and contour plots are not as important for this application. Ground deposition computation or output is not important for worker safety and emergency response for vapors concerns.
- **Time Averages:** Emergency planning lookup tables should consider peak concentrations. Thus, sub-minute concentrations are of highest concern, but average concentrations on time scales of 15 minutes (or longer) are also important for consequence analyses.
- **Usability:** Although intuitive user interfaces and easy-to-use software are appealing attributes, they are not critical for this application. Models should be validated, with accuracy information that is understood by the user.
- **Runtime:** Both fast setup and fast execution are not particularly important.

Table 3.5. Worker Safety and Emergency Planning Model Attribute Scores

Attributes	Weight (0-2)	Attributes	Weight (0-2)
Release Capability		Receptor Types	
Ground-Level Release	2	Discrete	2
Elevated Release	2	Cartesian Grid	1
Thermally Buoyant	1	Polar Grid	1
Momentum	1	Applicable Distance(s)	
Gas	2	≤100 m of release	2
Particles	0	100 m to 15,000 m	1
Point	2	15,000 m to 50,000 m	0
Area	1	≥50,000 m	0
Volume	1	Outputs	
Line	0	Air Concentration	2
Models Multiple Sources	1	Ground Deposition	0
Meteorological Capability		Text	2
Time Varying	1	Chart	1
Spatially Varying	1	Contour Plots	1
Real-Time Meteorology	0	Time Averages	
Historical Meteorology	2	≤1 minute	2
Inversion Layer	1	>1 minute	1
Fumigation	1	Usability	
Low Wind Speed	2	User Interface	1
Building Wake	2	Ease of Use	1
Stack-Tip Downwash	2	Validation/Accuracy	2
Dry Deposition	0	Runtime	
Wet Deposition	0	Fast Setup	1
Terrain Capability		Fast Execution	1
Uneven Terrain	2		
Terrain Steering	1		

Table 3.6 provides the overall model score from the worker safety and emergency planning model evaluation. Details of the model scores are included in Appendix F. These models were selected because they are either currently used in this application area or have attributes that point toward their value in this application area. The top four models for this application area are the FDS, CALPUFF, QUIC, and APGEMS models; three of these models happen to be the same three models (although in a different ranking order) as the top three models for the emergency response application. The FDS is a CFD model, which cannot be run quickly, so it was not included as an emergency response model. These models each treat a different spatial and temporal time scale. FDS and QUIC explicitly account for flow obstructions, so model setup requires additional information about physical structures that the other models do not require. The FDS model requires hours to produce a result, but the QUIC model runs relatively quickly

and produces output at a higher spatial and temporal resolution than CALPUFF or APGEMS. Both CALPUFF and APGEMS are puff models, which means they are normally applied at distances in excess of 100 m. APGEMS is distinct from CALPUFF in that it currently accepts real-time meteorology data from the Hanford Meteorological Network.

The fifth and sixth highest scores were for the ARCON96 and AIHA-Eddy models. ARCON96 is a plume model with a tuned dispersion coefficient, which typically improves concentration estimates for the nearest 100 m from the source. The time resolution for this model is hourly. The AIHA-Eddy model is distinctly different from the other models. This model diffuses a single puff released at a source location, so it is applicable for the nearest 5 to 10 m from the source. It will produce mathematical results for greater distances, but those results should not be considered valid output. This model is used by the tank farms Industrial Hygiene group to assess VCZ and VRZ boundaries, which are typically very near the source, and often within 5 to 10 m from the source, which is appropriate for this model. Although the turbulent eddy diffusion coefficient used for the tank farms applications appears to be based on indoor dispersion tests, which are related to air exchange rates, this approach results in conservative concentration values in the outdoor environment.

The AIHA-Plume model had the lowest score among this ranking. Although it is a simple plume model that runs quickly with limited user input, it implements Stability Class C, which means there is no mechanism within this model to account for other or more conservative (e.g., highly stable) stability conditions. It also exclusively presents output for distances less than 100 m, which is misleading because the formulations are based on the PG parameterization, which has no data to support these distances. Finally, the model implements the far-field (greater than 100 m) diffusion exponent rather than the mid-field (less than 100 m) diffusion exponent from the cited literature, which results in errors in the concentration that underestimate the plume concentration.

Table 3.6. Worker Safety and Emergency Planning Model Scores

Model	Total Score ^(a)	Model Type	Comments
FDS	79	CFD	Open-source CFD code for low-speed, thermally driven flow, with emphasis on smoke and heat transport from fires
CALPUFF	67	Puff	Not intended for sub-kilometer distances
QUIC	63	Particle	Explicitly accounts for flow obstructions (e.g., buildings)
APGEMS	52	Puff	Closest source to receptor distance – 100 m. Incorporates real-time data from the Hanford meteorological network.
ARCON96	51	Plume	NRC regulatory models with improvements for applications within several hundred meters of release
AIHA-Eddy	44	Puff	Maximum receptor distance is 5-10 m, used at the tank farms to establish VCZs and VRZs
EPIcode	42	Plume	Part of DOE Toolbox, in use at tank farms
ALOHA	41	Plume	Common for chemical releases
SAFER	39	Plume	Single source capability, was evaluated as part of pilot-scale testing at tank farms
AIHA-Plume	32	Plume	Single source plume model for near (0-3 m) and mid (3-100 m) field applications using average diffusion that is representative of Pasquill-Gifford “C” (slightly unstable) stability class.

(a) Maximum possible score (all attributes receive a value of 2) is 100.

3.3 Evaluation of Regulatory Compliance Models

Regulatory compliance models are used to estimate air concentrations at specific locations of interest, such as facility fence lines, public boundaries, or federal lands that are granted special air quality protections. Model-predicted averages are compared to defined air quality standards to determine compliance status. Typically, the regulating agency prescribes the model and methods to be used for estimating air concentrations. For example, the EPA has preferred models (40 CFR Part 51, Appendix W)—AERMOD and CALPUFF—that are required to be used in routine ambient air-quality permitting and compliance applications.

This regulatory model evaluation considers four EPA models: AERMOD, CALPUFF, SCIPUFF, and ISC. The EPA prescribes the use of AERMOD for all near-field (i.e., less than 50 km) ambient air-quality dispersion modeling applications (40 CFR Part 51, Appendix W). CALPUFF may be used on an “as-approved” basis for long-range transport (i.e., greater than 50 km) applications if impacts to national parks, national wilderness areas, or national monuments need to be considered (40 CFR Part 51, Appendix W). SCIPUFF is another EPA alternative model for certain approved applications. This model evaluation also considers the EPA’s ISC model. ISC had been the EPA’s preferred regulatory dispersion model; it has since been superseded by AERMOD (40 CFR Part 51, Appendix W). However, the Hanford tank farms use the results of a parametric study that is based on ISC (see Section 4.0); thus, ISC is considered in this evaluation.

Table 3.7 lists the attributes and corresponding weighting factors that were assigned in the regulatory model evaluation. Attributes with a weighting factor of 2 are considered highly important for regulatory modeling applications at the Hanford tank farms. The following considerations were used in developing the weighting factors for the regulatory model evaluation:

- **Release Capability:** The Hanford tank farms have both passive, ground-level and (elevated) actively-ventilated stack releases. These releases could have higher effective release heights due to thermal buoyancy or vertical momentum, which should be explicitly accounted for in regulatory modeling. The releases are assumed to be primarily in gas (vapor) phase, but other sources in solid (particulate) phase may be considered. Sources could be modeled as point, area, or volume sources, but likely not line sources, which are generally used for modeling roadways. Finally, multiple sources might need to be modeled across multiple tank farms.
- **Meteorological Capability:** Regulatory dispersion models use historical, time-varying meteorological datasets to estimate air concentrations; these datasets are normally hourly and span the latest 5-year period. The meteorological data is not real-time and would only be spatially varying if long-range transport (i.e., beyond 50 km) needed to be considered. The dispersion model should consider the inversion layer as a reflective boundary condition as well as account for unique meteorological conditions such as low wind speeds and, to a lesser extent, fumigation. Finally, factors affecting estimates within several hundred meters, such as building wake and stack tip downwash, should be considered. Deposition is not considered important for estimating tank farm vapor air concentrations.
- **Terrain Capability:** Regulatory dispersion models should account for uneven terrain, which leads to relative height differences between the release point and downwind receptor location. Terrain steering would only need to be considered in long-range (i.e., beyond 50 km) transport modeling applications.
- **Receptor Types:** Regulatory dispersion models should allow for discrete receptors to calculate air concentrations at specific locations or a Cartesian grid for a large area. A polar grid can be useful to cluster receptors near a release point, but this is generally not needed in regulatory modeling applications.

- **Applicable Distance(s):** Most regulatory dispersion modeling is for distances less than 50 km. Distances less than 100 m may be important if the facility fence line is near the release point. Distances greater than 50 km would only need to be considered in long-range transport modeling applications.
- **Outputs:** Text files are the standard way of outputting air concentrations for receptors; usually the output is in the form of tables of highest air concentrations at each receptor location. Contour plots can be useful to visualize the tabular data. Charts are generally not as useful because of the large number of receptors used in a model run.
- **Time Averages:** Regulatory dispersion modeling applications are concerned with 1-hour or greater time averages. The models do not need to account for short-term, peak concentrations (i.e., less than 1 hour).
- **Usability:** Regulatory dispersion models tend to be straightforward to use, but the interface and ease of use is not a critical attribute. However, their usability is enhanced through a GUI. Several third-party vendors (e.g., Trinity Consultants or Lakes Environmental) have created GUIs to the EPA's regulatory dispersion models. Model validation and accuracy are critical to the model's usability and for estimating accurate design air concentrations for a given release scenario.
- **Runtime:** Regulatory dispersion modeling applications may involve many sources and running multiple years (e.g., 5 years) of hourly meteorological data. Therefore, both model setup and runtime may take some time. However, this is generally not critical because the modeling is retrospective and does not need to be done in real-time.

Table 3.7. Attributes and Weighting Factors Used in the Regulatory Model Evaluation

Attributes	Weight (0-2)	Attributes	Weight (0-2)
Release Capability		Receptor Types	
Ground-Level Release	2	Discrete	2
Elevated Release	2	Cartesian Grid	2
Thermally Buoyant	2	Polar Grid	1
Momentum	2	Applicable Distance(s)	
Gas	2	≤ 100 m of release	2
Particles	1	100 m to 50,000 m	2
Point	2	≥ 50,000 m	0
Area	2	Outputs	
Volume	2	Air Concentration	2
Line	1	Ground Deposition	0
Allows Multiple Sources	2	Text	2
Meteorological Capability		Chart	1
Time Varying	2	Contour Plots	1
Spatially Varying	1	Time Averages	
Real-Time Meteorology	0	< 1 hour	0
Historical Meteorology	2	≥ 1 hour	2
Inversion Layer	2	Usability	
Fumigation	1	User Interface	1
Low Wind Speed	2	Ease of Use	1

Table 3.7 (cont.)

Attributes	Weight (0-2)	Attributes	Weight (0-2)
Building Wake	2	Validation / Accuracy	2
Stack-tip Downwash	2	Runtime	
Dry Deposition	0	Fast Setup	1
Wet Deposition	0	Fast Execution	1
Terrain Capability			
Uneven Terrain	2		
Terrain Steering	1		

AERMOD, CALPUFF, SCIPUFF, and ISC were scored against the attributes listed in Table 3.7; the model scores are provided in Appendix G. The attribute weighing factor (Table 3.7) was then multiplied against the corresponding model scores to determine a weighted-model score for each attribute. The weighted-model scores were then summed across all the attributes to determine the overall model score.

Table 3.8 provides the overall model score from the regulatory model evaluation. In general, the models performed equally well because the models were developed (or sponsored) by the EPA specifically for regulatory modeling applications. CALPUFF is the regulatory model for long-range transport (i.e., greater than 50 km) due to incorporation of spatially varying meteorology. For the spatial scales relevant to the regulatory needs at the Hanford Site, this spatial scale may be unnecessary. AERMOD is the preferred regulatory model because the EPA requires its use for all near-field (i.e., less than 50 km) applications. Furthermore, AERMOD incorporates recent theory on air dispersion that is based on planetary boundary layer turbulence structure and scaling concepts, and includes treatment of both surface and elevated sources, in both simple and complex terrain. The model has been extensively validated and tested as part of being promulgated as a regulatory model by the EPA. Therefore, AERMOD should be used in nearly all regulatory modeling applications, and is used for regulatory purposes at the Hanford tank farms.

Table 3.8. Overall Model Score from the Regulatory Model Evaluation

Model	Overall Score ^(a)	Model Type	Comments
CALPUFF	86	Puff	Applications > 50 km
AERMOD	84	Plume	Applications < 50 km, in use at tank farms
ISC	82	Plume	Superseded by AERMOD
SCIPUFF	81	Puff	EPA alternative model

(a) Maximum possible score (all attributes receive a value of 2) is 120.

3.4 Evaluation of Engineering and Research Models

Engineering and research models cover a broad range of modeling needs, such as evaluating the impact of varying stack heights, exploring the impact of stack velocities, and performing climatological evaluations of plume occurrence and concentration. This type of modeling may also provide a basis for creating confidence in applying models for real-time response, worker protection and emergency planning, and (perhaps to a lesser extent) regulatory purposes. Appendix H contains weighted scores for Fluent, CFX,

and STAR-CCM+ bundled together (since they have similar attributes), FDS, and MFiX to illustrate the differences between these codes. Other models, which may be used under the engineering and research umbrella, have been scored in this section as well.

The term *research models* often refers to more fundamental models such as CFD, but in the context of the tank farms, may also include the application of other recommended models for exploratory analyses or for model-to-model evaluations against codes such as CFD. For example, WRPS has performed CFD modeling alongside AERMOD modeling to evaluate stack height impacts and maximum plume concentrations. CFD models may also be used to produce reduced order models (ROMs), which aim to increase computational efficiencies by creating a simplified mathematical model that captures the primary physical processes of the detailed code. ROMs are a formal implementation of a process used to understand the most important physical processes driving the phenomena of interest. Engineering and research modeling may be used to explore these physical processes and their impacts on dispersion and tank farm operations.

Table 3.9 lists the attributes and corresponding weighting factors that were assigned in the engineering and research application area. Although engineering and research modeling applications may have a variety of different goals, spatial scales, and physical phenomena of interest, an overall summary of the attributes of interest for this application follows:

- **Release Capability:** The Hanford tank farms have both passive, ground-level and (elevated) actively-ventilated stack releases. These releases could have higher effective release heights due to thermal buoyancy or vertical momentum, but these effects are not expected to significantly influence concentration estimates. The releases are assumed to be in a gas (vapor) phase, not particulate. Sources could be modeled as point, area, or volume sources, but line sources are of lower importance for this application area. Finally, multiple sources might need to be modeled across multiple tank farms.
- **Meteorological Capability:** In the engineering and research space, historical or hypothetical meteorological data may be used, and real-time data would not be of importance. Time-varying meteorological data would be valuable for many applications within engineering and research. The spatial scale of the research interest would determine the appropriate spatial scale, and whether spatially varying meteorology should be considered. The dispersion model should consider the inversion layer as a reflective boundary condition as well as account for unique meteorological conditions such as fumigation and low wind speeds. Finally, factors affecting estimates within several hundred meters, such as building wake and stack tip downwash, should be considered. Deposition is not considered important for estimating tank farm vapor air concentrations.
- **Terrain Capability:** Engineering and research applications may not always need to account for uneven terrain based on the specific goals and spatial scales of the modeling activity. Dispersion at distances beyond the tank farm fence line should account for the elevation difference between the farm and the surrounding area. Terrain steering effects are likely to be of lesser importance at the spatial scales in this application.
- **Receptor Types:** In general, the arrangement of receptors is not a particularly high priority for this application area. However, specific applications may have strong preferences toward polar grids or Cartesian grids.
- **Applicable Distance(s):** It is anticipated that most engineering and research modeling is for distances less than 500 m. Distances less than 100 m may also be important if phenomena within a tank farm are explored. Regulatory far-field (i.e., greater than 50 km) distances would only need to be considered in long-range transport modeling applications.

- **Outputs:** Text files are the standard way of outputting air concentrations for receptors. Contour plots can be useful to visualize the tabular data. Charts may also be useful for finite receptors. Ground deposition computation or output is not important for vapors concerns.
- **Time Averages:** A variety of time scales may be of concern in this application area generally. However, in evaluating bolus events, time scales between tens of seconds to several minutes may be of highest interest.
- **Usability:** Although an ideal model would have a user-friendly interface and clear technical capabilities, model usability is not critical in this application. Models should be validated, with accuracy information that is understood by the user.
- **Runtime:** Under engineering and research, there are typically no time sensitivities to achieve a result, and model output analyses can be time consuming, so a fast runtime is not of high importance.

Table 3.9. Attributes and Weighting Factors Used in the Engineering and Research Model Evaluation

Attributes	Weight (0-2)	Attributes	Weight (0-2)
Release Capability		Receptor Types	
Ground-Level Release	2	Discrete	1
Elevated Release	2	Cartesian Grid	1
Thermally Buoyant	1	Polar Grid	1
Momentum	1	Applicable Distance(s)	
Gas	2	≤ 100 m of release	2
Particles	1	100 m to 15,000 m	2
Point	2	15,000 m to 50,000 m	1
Area	2	≥ 50,000 m	0
Volume	2	Outputs	
Line	1	Air Concentration	2
Allows Multiple Sources	1	Ground Deposition	0
Meteorological Capability		Text	2
Time Varying	2	Chart	1
Spatially Varying	1	Contour Plots	1
Real-Time Meteorology	0	Time Averages	
Historical Meteorology	2	≤ 1 minute	2
Inversion Layer	2	> 1 minute	2
Fumigation	2	Usability	
Low Wind Speed	2	User Interface	1
Building Wake	2	Ease of Use	1
Stack-tip Downwash	2	Validation / Accuracy	2
Dry Deposition	0	Runtime	
Wet Deposition	0	Fast Setup	1
Terrain Capability		Fast Execution	1
Uneven Terrain	1		
Terrain Steering	1		

The commercial CFD codes, FDS, and MFiX as well as QUIC, AERMOD, and ARCON96 were scored against the attributes listed in Table 3.9; the model scores are provided in Appendix H. The attribute weighting factor was then multiplied against the corresponding model scores to determine a weighted-model score for each attribute, which were then summed to determine the overall score presented in Table 3.10. A variety of specific applications are possible within the broad umbrella of engineering and research applications, so these few models were selected as a limited comparison to illustrate some model differences. Specific goals of each particular application will determine the model that is truly most appropriate for the application.

The FDS CFD code had the highest overall score, followed by the commercial CFD codes, AERMOD, and MFiX. For applications where high temporal and spatial resolution is needed and the effects of flow obstructions (i.e., buildings) are important, CFD or QUIC (which had the fourth highest score) provides the most detailed dispersion information. CFX was used by AREVA to support stack height evaluations. FDS is currently used by Kenexis to support sensor placement, and had a score that was slightly higher than the commercial CFD codes based, in part, on the ease of prescribing area and volume sources without creating the sources within the mesh and re-meshing the domain. The open-source MFiX code, which does not support unstructured mesh, would be impractical for tank farms applications. AERMOD is also used at the tank farms for a variety of engineering topics, including stack height evaluations. ARCON96 may provide more realistic plume estimates than AERMOD in the nearest 100 m from the source due to added dispersion enhancements in this region.

Table 3.10. Overall Model Score from the Engineering and Research Model Evaluation

Model	Overall Score ^(a)	Model Type	Comments
FDS	91	CFD	Open-source CFD code for low-speed, thermally-driven flow, with emphasis on smoke and heat transport from fires
Fluent, CFX, STAR-CCM+	87	CFD	Commercial CFD code for a variety of applications; CFX has been used in tank farms
AERMOD	79	Plume	EPA regulatory model for near-field (i.e., <50 km) applications, in use at tank farms
MFiX	78	CFD	Open-source CFD code for multi-phase flows
QUIC	72	Particle	Explicitly accounts for flow obstructions (e.g., buildings)
ARCON96	58	Plume	NRC regulatory model with improvements for applications within several hundred meters of release

(a) Maximum possible score (all attributes receive a value of 2) is 116.

3.5 Tank-Farm-Specific Applications

A general ranking of models for relatively broad application areas has been presented to illustrate the qualities of the various models examined in this work; however, selection of the most appropriate model for a given application must consider the specific needs for each specific application. Table 3.11 presents

a summary of models that are recommended for a selection of specific model applications from the tank farms. This is not a comprehensive list of the atmospheric dispersion modeling needs for the tank farms, but illustrates how model selection may be made, based on the requirements of the application.

Although the CALPUFF model ranked highly in the broad application areas where it was ranked, it does not appear as a recommended model in Table 3.11. This is because the model is intended for transport problems of tens to hundreds of kilometers, which is beyond the spatial scale of interest for the tank farms, which is often within tens of meters, but may be up to several kilometers from a source. Additionally, while the environmental compliance application might consider the CALPUFF model, the terrain and meteorology for this region is not particularly complex, so the AERMOD plume model is the preferred EPA model for this site.

As noted in the description of plume and puff models, Gaussian models are not accurate for the nearest 100 m from a source. Since many tank farms applications are interested in spatial scales from tens to hundreds of meters, models that address near-source concentrations, such as QUIC or CFD, are commonly recommended in Table 3.11. In certain instances, although Gaussian models may be imprecise in the nearest 100 m, APGEMS is recommended based on its strengths in fast setup, fast runtimes, and ease of operation. The approximate results that APGEMS produces at these distances may be of value in AOP-015 investigations and emergency planning.

Modeling is often one of several tools used by the tank farms operator in applications such as assessing VCZs and UWBs. Other applications, such as stack height evaluations, utilize modeling exclusively due to the nature of the investigation (although follow-on measurements may be made after stack-height modifications are complete). For these applications, CFD may be used for specific case studies, but the ability to incorporate a wide range of meteorological conditions through multi-year input files is a practical method for assessing the impact of stack-height modifications.

Table 3.11. Summary of Model Recommendations for Specific Tank Farms Application Areas

Application Area	Recommended Model(s)	Notes
Environmental Compliance	AERMOD	AERMOD is the EPA-recommended model for environmental permitting and compliance needs.
Establish VCZs	QUIC, CFD (e.g., FDS)	Based on the typical distance between the emission source and the VCZ boundary (<10 m), models that adequately address near-source concentrations are needed.
Establish UWBs	QUIC, CFD (e.g., FDS)	Based on the typical distance between the emission source and the UWB (<100 m), models that adequately address near-source concentrations are needed.
Stack Height Evaluation	AERMOD, CFD (e.g., FDS)	AERMOD is a practical option for evaluating impacts of varying stack heights under a broad range of environmental conditions. CFD may be used for specific cases, but is typically too computationally intensive to assess numerous atmospheric conditions.
AOP-015 Investigations	APGEMS, QUIC, CFD (e.g., FDS)	For the nearest 100 m from a source, models that adequately address near-source concentrations, such as QUIC or CFD, will provide the most physically realistic result. APGEMS does not provide reliable results at <100 m, but provides a general sense for the plume position, and runs quickly.
Sampling Location Strategy	QUIC, CFD (e.g., FDS)	Based on the typical distance between the emission source and worker locations (<200 m), models that adequately address near-source concentrations are needed. A quantitative risk assessment approach is an appropriate and rigorous process to inform air sampling locations.
Emergency Planning	EPIcode, APGEMS, QUIC, CFD (e.g., FDS)	EPIcode is in the DOE Toolbox for emergency preparedness hazards assessments, and is the suggested model for evaluating chemical hazards. APGEMS does not provide reliable results at <100 m, but provides a general sense for the plume position, and runs quickly. Other emergency planning applications, particularly when considering distances <100 m, require models that adequately address near-source concentrations, such as QUIC or CFD. A quantitative risk assessment approach with these models is also recommended.

UWB = unrestricted work boundary

3.6 Model Validation for the Tank Farm Environment

Although most models have undergone a quality assurance (QA) process prior to being published, the QA approach may range from exercising the code to identify and correct software bugs, to performing extensive model comparisons with field data to refine the equations in the code. For all dispersion model applications described in this report, evaluating models specifically for use in the tank farm environment would have significant value. The specific features that may be unique to the tank farms, and therefore motivate a validation study, include high temporal resolution needs, the variety of flow-obstructing structures near some stacks, effects of elevation on receptor concentrations, and the potential for unique atmospheric conditions.

A standard approach to model validation is performing a series of tracer tests. Executing a successful tracer study is not a trivial effort, and extensive planning is necessary to ensure that the goals of the study will be met. Logistical considerations, such as the ability to release gases within the tank farms and the ability to retrieve equipment from the tank farms, will also constrain the test design.

Overall, a tracer study involves the prescribed (instantaneous or continuous) release of a non-reactive gaseous compound and the measurement of this compound at varying downwind locations. To ensure that the atmospheric conditions of the test are well-characterized, meteorological measurements should be made specifically for the tests. At a minimum, wind speed, wind direction, temperature, and relative humidity at a single point are required. Additionally, these measurements at multiple locations or in a vertical profile may be beneficial. Solar radiation and turbulence measurements may also inform the dispersion characteristics during the tracer release. Meteorological input needed for the model(s) under validation should also be included.

Ideally, a tracer test would collect tracer concentration data at a higher temporal frequency than the model output. Additionally, a sampler deployment strategy would need to be developed to focus on the goal of the modeling and the physical processes of interest. One approach is to install samplers at a spatial density that is higher than the spatial scale of concern. For example, if tank farm spatial scales were of interest, a farm could be divided into several sections, with one or more sampling locations within each section to evaluate concentration variability. Furthermore, a combination of discrete measurement points as well as integrated plume measurement (e.g., open path instruments) would be desirable. Field measurements are unlikely to capture the plume centerline due to varying meteorological conditions, and an integrated plume concentration measurement in conjunction with the point measurements provides a sense of the plume width and perhaps the centerline concentration.

Finally, the tracer tests should be conducted under several sets of meteorological and release conditions such as varying wind speed, days versus nights, and ground-level versus elevated releases. While a sensitivity analysis could identify the worst conditions for dispersion, testing several conditions would inform users on the model function under varying conditions, and in turn ensure that this understanding translates to protection of workers under all conditions. Although it may pose a logistical challenge, aiming to perform a tracer study during conditions that are associated with a higher likelihood of exposure events may also be beneficial.

For models that are developed by other organizations, implementing changes into the code based on a tank farm tracer study may be unlikely. However, the tracer study itself provides valuable data regarding dispersion in the tank farm environment and illustrates limitations of specific models for specific cases. APGEMS has been developed at PNNL, and model development for the tank farms has begun in FY 2017; however, changes are limited to model capabilities, and no changes will be made to the source code

itself. Additionally, CFD codes allow user-defined functions, which may allow for model improvements without changing the source code itself.

4.0 Evaluation of a Parametric Plume Model Study

The Droppo (2004) parametric study aimed to provide a simple evaluation of mean concentrations as a function of downwind distance for a set of discrete wind speed and atmospheric stability conditions. The plots and tables in the Droppo report provide a relatively quick and easy way to estimate mean concentrations based on current meteorological conditions. Because a decade has passed since the Droppo (2004) analysis was completed, an evaluation using the current EPA regulatory model, AERMOD, was performed. This reanalysis of the Droppo work had two main purposes. The first was to provide a qualitative evaluation of the applicability of the concentration values modeled by Droppo, in light of an updated dispersion model. Second, this evaluation provided an opportunity to examine potential shortcomings of using concentrations from either the Droppo work or the AERMOD reanalysis as guidance in the tank farms. A description of the Droppo report is included in Section 4.1. The details concerning comparison with AERMOD are included in Section 4.2. Finally, concluding remarks and model limitations are discussed in Section 4.3.

4.1 Droppo Parametric Study

Droppo (2004) describes a parametric study of the relative concentrations of vapors (fraction of initial concentration) that could occur at discrete distances from release points as a function of various meteorological conditions (stability class and wind speed pairs) and release configurations (PBFs, actively ventilated stacks). The emphasis of that analysis was to understand the magnitudes and mechanics of potential exposures to workers in the immediate area downwind of the tank vents and stacks (i.e., exposures within several hundreds of meters). Time-averaged concentrations were based on a simple Gaussian plume equation, using a spreadsheet. The potential for tank plumes to rise from thermal buoyancy or momentum was evaluated with equations from the ISC model. Plume rise effects were minimal, and thus were not accounted for in the plume equation.

The Droppo work evaluated breathing zone concentrations (1 m above ground level) as well as plume centerline concentrations at wind speeds of 1.0, 3.4, 10.0, and 20.0 m/s, each at various stability classes. Each stack considered in the analyses was modeled with unique release rates based on reported flow rates or personal communications. The results were summarized in plots that illustrate the ground level and plume centerline concentration as a function of downwind distance as well as with data tables. WRPS has used the results of the Droppo work as guidance concerning distances to peak concentrations (Meacham et al. 2006).

General conclusions from the Droppo report include the following:

- At distances less than approximately 100 m, the maximum concentration is bounded by the headspace concentrations.
- There is little possibility of significant momentum or thermal plume rise from vapor releases. Stack wakes typically reduce the plume height.
- For stack releases, the plume centerline will normally travel above the breathing zone in a tank farm. Under special cases of fumigation, plumes may be carried down into the breathing zone. Elevated plumes may intercept the breathing zone when the nearby terrain is elevated relative to the farm.
- The touch down point for stack releases consistently occurs when the average concentration has been reduced by at least 3 or 4 orders of magnitude.
- Plume pooling is not expected; release volumes are sufficiently small that density effects are not a factor.

- Combinations of plumes are generally unlikely. For most conditions, the tank plumes disperse so quickly that the additive effects of plumes combining are negligible.

Additional points from the relative concentration tables presented in Droppo (2004) are as follows:

- For stack releases, the plume reaches ground level at distances of 30 m or more, with the actual plume touch down distance dependent on meteorological conditions.
- For stack releases, the highest relative ground level concentrations at 30 m would occur during Pasquill A or B (very unstable or unstable) conditions.
- For near-surface releases, the highest concentrations at any distance occur during stable conditions with low wind speeds.
- With all other factors being equal, higher stacks and lower stack emission rates result in lower downwind concentrations.

4.2 Case Study Comparisons

The Droppo (2004) analysis was performed using algorithms based on the EPA's ISC (EPA 1995) dispersion model. At the time, ISC was the EPA's preferred regulatory dispersion model; it has since been superseded by AERMOD (EPA 2004a). Although AERMOD and ISC are both plume models (see Section 2.1), they differ significantly in their treatment of atmospheric dispersion. ISC uses the Briggs (1974) dispersion formulations, which parameterize atmospheric diffusion as a function of discrete atmospheric stability classes (A [extremely unstable] through F [extremely stable]) and downwind distance from the release. AERMOD, however, uses direct measurements or estimates of turbulence to construct vertical profiles of horizontal and vertical diffusion coefficients using boundary layer similarity theory. The vertical profiles are then averaged between the plume and receptor heights to estimate "effective" diffusion coefficients. Thus, AERMOD treats diffusion continuously and, using vertical averaging, explicitly accounts for known vertical inhomogeneity in boundary layer turbulence.

Since ISC and AERMOD treat atmospheric dispersion differently, a limited evaluation was performed to better understand how these differences might affect conclusions drawn from the Droppo (2004) analysis. Table 4.1 summarizes cases from the Droppo work that were selected for this limited case study. These cases were chosen to cover a range of release heights and ventilation rates. A PBF with low ventilation rate (near-surface vent), a moderate height actively ventilated stack (AP Farm), and a taller actively ventilated stack (AY Farm) were simulated.

The cases listed in Table 4.1 were first modeled in ISC and compared to the Droppo results. Since the Droppo (2004) analysis is based on algorithms found in ISC, modeling the cases in ISC first helps confirm that the model inputs are correct and appropriately applied. Next, the same cases were modeled in AERMOD. Except for the meteorology, AERMOD and ISC were designed to have similar inputs, allowing for relatively simple model-to-model comparisons. With regard to meteorology, ISC uses discrete wind speed and stability class values. AERMOD, however, uses planetary boundary layer scaling parameters. These parameters are continuous and have a range of values for a given discrete ISC wind speed/stability class. Therefore, to perform the comparison, the ISC meteorological inputs of wind speed and stability class were mapped to representative discrete AERMOD boundary layer parameters, including friction velocity (u^*), convective velocity (w^*), surface heat flux, and Monin-Obukhov length values. Parameters such as surface roughness, Bowen ratio, albedo, and atmospheric pressure also needed to be prescribed for the AERMOD cases. The meteorological input files for ISC and AERMOD are included in Appendix I. The meteorological input files are based on the data used in Droppo (2004) and

include 20 hourly meteorological realizations, using a combination of stability classes and wind speeds that ranged from 1 to 20 mph.

Table 4.1 summarizes the five cases that were selected for this limited model comparison, along with a bulk comparison of the concentration results. These bulk comparisons were made at specific downwind distances where the concentration comparison was deemed “fair.” This generally meant that the two models agreed that the plume had touched-down to the surface in the case of ground-level concentration (GC) comparisons. Typical distances over which these comparisons were made were from 10 to 100 m through 10 km. Tables summarizing the relative concentrations from the ISC and AERMOD model runs against the Droppo (2004) results at discrete downwind distances for each stability class included in the model runs are also provided in Appendix I.

Table 4.1. Selected ISC and AERMOD Comparisons with Droppo (2004) Results

Release Configuration	Release Height (m)	Ventilation Rate (m ³ /hr)	Receptor Height ^(a)	Avg Ratio of ISC to Droppo Concentration ^(b)	Avg Ratio of AERMOD to Droppo Concentration ^(b)
Near Surface Vent	1	1	GC	4.2E-01	5.3E-03
AP Farm	6	1359	GC	5.2E-01	4.2E-03
AP Farm	6	1359	CC	4.5E-01	2.7E-03
AY Farm	16.7	1699	GC	5.4E-01	1.7E-02
AY Farm	16.7	1699	CC	4.7E-01	2.3E-02

(a) GC refers to ground-level (1 m) concentrations, while CC refers to plume centerline concentrations. For the near-surface vent, GC = CC.

(b) This ratio is the average of discrete points where concentration comparisons were deemed “fair,” often starting at 10 to 100 m from the source, for all wind speed and stability conditions modeled.

The ISC results show that the Droppo concentration estimates are conservative, with values about a factor of two higher than the ISC modeled concentrations. Since Droppo and ISC are based on similar algorithms and have similar meteorological inputs, this difference in predicted concentrations is reasonable. For context, in Gaussian plume modeling, model-to-model comparisons of spatially and temporally varying concentrations are said to compare well when their results are within a factor of two. The AERMOD results, however, are significantly lower than the ISC and Droppo results. This result is not what was initially expected, given that AERMOD is the most current EPA regulatory model, following ISC. Significant effort went into developing AERMOD to ensure that regulatory outcomes would not be significantly different as a result of the new model implementation. As described previously, AERMOD differs significantly in its treatment of atmospheric dispersion and requires much more meteorological input. The differences in hourly concentrations are likely attributed to differences in dispersion, but also the mapping of meteorological inputs between the models.

As part of promulgating AERMOD, the EPA performed numerous ISC-to-AERMOD comparisons to ensure regulatory stability between the two codes (e.g., see EPA 2003). The model comparisons focus on “design” concentrations—that is, average concentrations estimated from a range of meteorological conditions over a long statistical time period (e.g., a year to years of hourly realizations)—instead of concentrations determined from individual, hourly realizations. For example, the maximum model concentrations for the 1-, 3-, 24-hour, and annual averaging periods would be compared at a given location; however, these maximum concentrations do not need to occur during the same meteorological time period.

Results from the EPA model comparisons show that ISC and AERMOD provide comparable statistical “design” concentrations, and are generally within a factor of four. However, as this limited Droppo-to-AERMOD comparison illustrates, the models can differ dramatically for a given hourly realization. As a result, the poor comparison from this limited evaluation does not indicate whether one model is more appropriate than the other, but illustrates the shortcomings in implementing a comparison in this way. As a result, a follow-on effort that uses several years of local meteorological data, and compares these “design” concentrations with the Droppo (2004) work, is recommended.

4.3 Case Study Limitations and Considerations

Evaluating the Droppo (2004) work alone, as well as with the ISC and AERMOD results, illustrates the fact that all models have limitations, and that understanding these limitations is important when interpreting and using model results. Although many of the limitations discussed below have been noted in Section 2.1, some specificity is included in the following model limitations and considerations.

- **Discrete Wind Speed and Stability Class Pairs:** The parametric approach in the Droppo analysis provided tables that were easy to use, given a wind speed and stability class, which are readily available from the Hanford Meteorological Station. However, these discrete cases do not represent the broad range of atmospheric conditions that can exist within a given wind speed and stability class pair, and make no distinction about the likelihood that any particular wind speed and stability class combination would occur at the tank farms. An evaluation that uses multiple years of historical meteorological conditions to develop a cumulative distribution function of downwind concentrations and frequencies and magnitudes of worst case conditions for the time-averaged concentration values is recommended. Performing this type of analysis with AERMOD would develop the range of meteorological conditions necessary to apply a more appropriate comparison between the Droppo and AERMOD results as well.
- **Assumed Release Configurations:** The release configuration (stack heights and release rates) has a direct impact on downwind concentrations. The double-shell tank ventilation systems and stacks have been modified since 2004, and passive ventilation rates were based on tracer studies conducted in the 1990s (Huckaby et al. 1997), and may differ now due to changes in process, content, and chemical changes in the tanks.
- **Steady-State Release Conditions:** Plume models predict downwind concentrations from steady-state meteorological conditions (constant wind direction, wind speed, and release rates). While modeling steady-state release conditions may be appropriate for double-shell tanks with active ventilation, modeling time-varying emission rates may be more appropriate for passively ventilated stacks, which are not steady and continuous, and are driven by environmental factors, such as wind speed and barometric pressure (Huckaby et al. 2004), as well as tank process factors. Fugitive emissions may also occur as puff releases rather than continuous releases.
- **Time-Averaged Concentrations:** Plume models also provide time-averaged concentrations that typically represent 15-minute to 1-hour averages, which can be much lower than short-duration peak concentrations. Droppo (2004) describes peak-to-mean ratios of 2 to 10. Turner (1994) presents research from a few investigators and notes that 30-second averages can be 4 to 10 times larger than the 1-hour average.
- **Transient Transport Phenomena Not in Models:** Models attempt to capture the most relevant physical processes, but some transport phenomena, particularly transient phenomena, may not be incorporated in standard dispersion models. For example, the worst case dispersive conditions in the nearest several hundred meters may be very different than the worst case conditions for dispersion farther downwind. Under unstable conditions, large turbulent eddies may form and pass over a ventilating

stack, effectively transporting an un-diluted puff of tank headspace vapor. Unstable conditions are generally regarded as good for “average” dispersion, and for long time periods and more distant receptors, this is generally the case. However, turbulence and fumigation are difficult to predict, so operators must understand the potential meteorological conditions of concern that are not typically reflected in model outputs. The relative concentration tables in the current analysis do not address transient phenomena.

- Source Term Uncertainties: Other source attributes that are not well understood, particularly for tank farm emissions, include chemical composition of the tank emissions. Tank headspace concentrations have been characterized during specific measurement campaigns, but the variation of emissions concentrations over time has not been well documented.

5.0 Conclusions

This report summarizes atmospheric dispersion models and dispersion modeling application areas as they relate to the modeling needs and priorities for the Hanford tank farms. Although a variety of application areas exist, the focus of the TVAT is predicting or responding to short-duration exposures (seconds to minutes) to elevated concentrations of chemical vapors, termed bolus events. Four categories of modeling applications have been presented in this report, and three of these areas (real-time response, worker safety and emergency planning, and engineering and research applications) are most appropriate for addressing bolus events.

- A real-time response model aims to determine the plume size and location; its use is initiated by a reported exposure or a real-time sensor alarm. A typical goal of this type of modeling is to direct personnel away from a hazard, and to identify whether the hazard is still present.
- Worker safety and emergency planning applications include the use of models to plan worker evacuation strategies in the event of elevated concentrations, evaluate the likelihood of unfavorable atmospheric dispersion conditions, and establish VCZs and VRZs.
- Engineering and research applications are a broad range of activities that include assessing the impacts of changing engineering controls, meteorological or process conditions, and other stack or fugitive emissions characteristics.

The final model category, regulatory applications, does not directly address chemical vapor exposure concerns at the tank farms. This category is typically concerned with estimates of facility fence line concentration extremes on an annual basis.

When selecting a model for a particular application, it is important to understand the strengths and limitations of the class of model (plume, puff, particle, or CFD), as well as the strengths and limitations of the specific model in question. Models can provide value in developing relationships between atmospheric conditions and concentrations in a systematic way, which is not practically achieved with measurements. However, most models do not capture the transient nature of plume concentrations. As a result, short-duration (from seconds to minutes) peak concentrations at a receptor location must be considered separately. In addition, users must understand the atmospheric processes that are not captured by models when interpreting the model results.

The model summary and evaluation effort presented in this report is focused on dispersion models of chemical emissions, and does not include discussions of models that exclusively treat radiological emissions or models that include chemical reactions. Chemistry models are a separate class of models, and the typical atmospheric chemistry incorporated by these models is not likely to be relevant to tank vapors. This study also does not explicitly address models that perform back-calculations from receptors to identify likely source locations. One of the particle models discussed in the report, HYSPLIT, does include a back-trajectory capability that is commonly used for long-range transport studies, but few models perform back-trajectory calculations for the spatial scales of the tank farms.

A model ranking method was applied to score models for real-time response, worker safety and emergency planning, regulatory, and engineering and research applications as presented in Table 5.1 through Table 5.4. Note that the total maximum score is different for each model application because model features are weighted differently according to the priorities of each application. As a result, the score for any particular model is different for each application area. For example, CALPUFF has a score of 70 for real-time response applications, 67 for worker safety and emergency planning, and 86 for regulatory applications. Also note that the ranking process applied a 0-2 weighting for each model attribute, which means that no single attribute would drive a high or low model score. If one or two model

attributes are particularly important to an application area, the specific model score for that attribute should be assessed prior to making final conclusions about the model suitability.

The models selected for the real-time model application area (Table 5.1) are models that are currently used in this application by government agencies or industry. The top three models for this area are CALPUFF, APGEMS, and QUIC. Some of the distinguishing characteristics among these models are that APGEMS only allows point sources (no volume, line, or multiple sources). APGEMS, however, currently accepts real-time meteorology from the Hanford Meteorological Network. Both APGEMS and CALPUFF are puff models, so they are generally applied for distances in excess of 100 m, but results from these models can provide value concerning plume direction and concentration within 100 m. The QUIC model, on the other hand, is a particle model that explicitly accounts for flow obstructions, and is designed to run quickly for domains that are on the order of hundreds of meters. QUIC can provide more refined plume concentration estimates at higher temporal resolution than APGEMS or CALPUFF. Finally, APGEMS was developed at PNNL, and model development for the tank farms began in FY 2017.

Table 5.1. Real-Time Model Scores

Model	Model Type	Total Score
CALPUFF	Puff	70
APGEMS	Puff	66
QUIC	Particle	66
ADAPT/LODI	Particle	60
HYSPLIT	Particle	60
EPIcode ^(a)	Plume	50
ALOHA	Plume	49
SAFER ^(b)	Plume	44

(a) Used in tank farms, although only for planning and not for real-time response.

(b) Was under evaluation for use in the tank farms.

The models selected for the worker safety and emergency planning application area (Table 5.2) are models that are used in this application by government agencies, the tank farms, or industry. The top four models for this application area are FDS, CALPUFF, QUIC, and APGEMS; three of these models happen to be those that were ranked highest for the real-time application. FDS was not included as an emergency response model because it is a CFD model that cannot be run quickly. For applications that require concentration estimates within 100 m of an emission point, a CFD model such as FDS or the particle model QUIC will provide the most physically realistic solution, with the ability to prescribe a temporal resolution that is appropriate for vapor events.

The fifth and sixth highest scores were for the ARCON96 and AIHA-Eddy models. ARCON96 is a plume model with the advantage of enhanced diffusion coefficients, which typically improves concentration estimates within 100 m of the source. The time resolution for the ARCON96 results is hourly. The AIHA-Eddy model is distinctly different from the other models. It diffuses a single puff released at a source location, with a single turbulent eddy diffusion coefficient for the horizontal and vertical directions. This is because the model was designed for indoor releases, as stated in AIHA 2009. Since the atmosphere is not radially symmetrical, the AIHA-Eddy model is most appropriate for the nearest 5 to 10 m from the source. This model is used by the tank farms Industrial Hygiene group to assess VCZ and VRZ

boundaries, which are typically very near the source, making this use of the model appropriate. The turbulent eddy diffusion coefficients used in the model are conservative for outdoor environments.

SAFER generally performs poorly in these rankings because it doesn't treat many unique conditions that may be important at the tank farms, such as low wind speeds, building wakes, or stack-tip downwash. Additionally, the user interface can be confusing, and model output is not readily exported. However, dispersion modeling is one part of the overall scope of this software, which includes sensor data archival and real-time data display. These other software features are fairly unique for off-the-shelf software, and allow users to quickly assess sensor data deployed as part of a network of sensors.

The AIHA-Plume model scored lowest in this ranking. It is a simple plume model that runs quickly, but has some deficiencies. This includes the implementation of only Stability Class C data output for distances less than 100 m when there is no data to support model approximations for these distances, and an error in the diffusion exponent that underestimates the plume concentration.

Table 5.2. Worker Safety and Emergency Planning Model Scores

Model	Model Type	Total Score
FDS	CFD	79
CALPUFF	Puff	67
QUIC	Particle	63
APGEMS	Puff	52
ARCON96	Plume	51
AIHA-Eddy ^(a)	Puff	44
EPIcode ^(a)	Plume	42
SAFER ^(a)	Plume	41
ALOHA	Plume	39
AIHA-Plume ^(a)	Plume	32

(a) Used (or in the case of SAFER, was under evaluation for use) in tank farms.

The models selected for the regulatory model application area (Table 5.3) are all EPA-recommended (or previous EPA-recommended) models. These models are not expected to directly address chemical vapor exposure concerns at the tank farms. However, the scores are presented for completeness with respect to the material presented in this report. The scores for these models are all very similar, which is expected, since the EPA drives similar model attributes for their regulatory models.

Table 5.3. Regulatory Model Scores

Model	Model Type	Overall Score
CALPUFF	Puff	86
AERMOD ^(a)	Plume	84
ISC	Plume	82
SCIPUFF	Puff	81

(a) Used in the tank farms.

Although a variety of specific applications are possible within the broad umbrella of engineering and research applications, a few models were selected for comparison; these are included in Table 5.4. More than any other application category, the specific goals of the particular engineering and research application will determine which model is truly most appropriate, rather than the rankings presented here. The FDS code had the highest overall score, followed by the commercial CFD codes and AERMOD. FDS provides features to simplify and accelerate simulation setup, and was used by Kenexis for the quantitative risk analysis at the A and AP tank farms. Among the commercial CFD codes, CFX was used by AREVA to compare the effect of varying stack heights with AERMOD. It is appropriate to use CFX and AERMOD for this specific application.

Table 5.4. Engineering and Research Model Scores

Model	Model Type	Overall Score
FDS ^(a)	CFD	91
Fluent, CFX ^(a) , STAR-CCM+	CFD	87
AERMOD ^(a)	Plume	79
MFiX	CFD	78
QUIC	Particle	72
ARCON96	Plume	58

(a) Used in the tank farms.

Model recommendations for a selection of dispersion modeling applications employed for the tank farms are listed in Table 5.5. The ranking method described above illustrates model capabilities and how they align with general categories of model applications. However, Table 5.5 presents recommendations that consider the specific needs of specific model applications. As a result, the CALPUFF model, which ranked highly in several of the broad application areas, is not included in the tank farms recommendations due to the spatial scales for which the CALPUFF model is designed. The tank farms modeling needs are often for distances that are tens to hundreds of meters from a source. For these distances, Gaussian models are not expected to provide accurate results. Instead, models that are more appropriate for these distances, such as QUIC or CFD, are recommended.

Table 5.5. Model Recommendations for Tank-Farm-Specific Applications

Application Area	Recommended Model(s)
Environmental Compliance	AERMOD
Establish VCZs	QUIC, CFD (e.g., FDS)
Establish UWBs	QUIC, CFD (e.g., FDS)
Stack Height Evaluation	AERMOD, CFD (e.g., FDS)
AOP-015 Investigations	APGEMS, QUIC, CFD (e.g., FDS)
Sampling Location Strategy	QUIC, CFD (e.g., FDS)
Emergency Planning	EPIcode, APGEMS, QUIC, CFD (e.g., FDS)

A model validation study would have significant value as part of implementing a dispersion model for operational use at the tank farms. This report discusses model strengths and weaknesses, as well as the dispersion modeling needs at the tank farms. Executing a tracer study at or near the tank farms provides ground-truth data to illustrate these strengths and weaknesses for specific test cases. This report described a general overview of such a tracer study, since a successful tracer study requires detailed planning to achieve specific objectives.

The final component of this report was a limited evaluation of a parametric study (Droppo 2004) to assess the need to update the analysis with the latest EPA-recommended dispersion model. Atmospheric dispersion is treated very differently between the stability class approach used by Droppo (2004) and ISC and the boundary layer similarity approach within AERMOD. As a result, the Droppo work and ISC simulations compared within a factor of four, but the AERMOD simulations had large differences that diverged with downwind distance. These large differences between these models are a result of these fundamental differences in the model inputs. The attempt to map the Droppo (2004) stability classes to AERMOD boundary layer similarity input results in a comparison of individual model realizations. AERMOD is designed to produce statistically averaged results, and is not meant to be used for case study evaluations. Therefore, a meaningful conclusion cannot be made from this comparison.

Alternatively, developing an input file with several years of onsite data to develop the statistical output that is the intended AERMOD output would be a more appropriate method to update the Droppo work. The added value of a rigorous study with AERMOD is that the results may be analyzed for additional details, such as the frequency of occurrence of low-dispersion conditions, peak concentrations, and typical concentrations. Note, however, that the peak concentrations produced by a model such as AERMOD represent hourly averaged values, and peak concentrations at higher temporal resolutions may be an order of magnitude higher than these hourly values. Additionally, certain meteorological phenomena that may result in the transport of nearly undiluted headspace concentrations that are not captured by plume models. These conditions include cold winter mornings with low inversions as well as hot summer days with large thermal eddies.

Recommendations for future work to implement appropriate modeling tools for tank farms include the following:

- Consider the operational use of APGEMS at the tank farms to regularly estimate plume location based on estimates of release positions and emission rates. Since this model is developed by PNNL, tank-farm-specific meteorological stations and source term libraries specific to the tank farms can be incorporated to help improve plume estimates.

- Incorporate a high spatial- and temporal-resolution model such as FDS or QUIC for applications within 100 m of a source.
- If a comparison with the Droppo (2004) work is needed, this should be performed with an AERMOD study with 5 years of local meteorological data for selected release locations to evaluate the concentration output. Although this type of AERMOD simulation has been performed by WRPS as part of regulatory requirements and engineering and research efforts, the output has not been analyzed for a parametric study comparison, nor has it been evaluated for the frequency of occurrence of potentially low-dispersion conditions.
- Discontinue the use of the SAFER software based on the result of pilot-scale testing for the tank farms.
 - Other models that are selected for tank farms use (in lieu of SAFER) should be accompanied by clear documentation of the dispersion model limitations.
- Develop a limited wind library with CFD software to evaluate the impact of structures on concentrations, and to evaluate the utility of wind libraries (i.e., pre-computed wind fields) to quickly produce concentration estimates for real-time response applications.
 - The model simulations performed by Kenexis for sensor placement needs may be used for wind library evaluations as well.
- Assess the needs and goals of a tracer study to evaluate a model or models selected for use at the tank farms. Design and execute a tracer study based on the model(s) under evaluation and the specific goals of using these models.

6.0 References

40 CFR Part 51, Appendix W, Guideline on Air Quality Models.

AIHA. 2009. *Mathematical Models for Estimating Occupational Exposure to Chemicals*, 2nd Edition, C Keil, editor.

ANSYS, Inc. 2015. *ANSYS Fluent User's Guide*. Canonsburg, PA.

ANSYS, Inc. 2016. *ANSYS CFX-Solver Theory Guide*. Canonsburg, PA.

Briggs GA. 1974. *Diffusion Estimation for Small Emissions*. Environmental Research Laboratories Air Resources Atmospheric Turbulence and Diffusion Laboratory 1973 Annual Report, USAEC Rep. ATDL-106, National Oceanic and Atmospheric Administration, Washington, D.C.

CD-adapco. 2016. *STAR-CCM+ v11.04 User Guide*.

DOE. 2004. *EPIcode Computer Code Application Guidance for Documented Safety Analysis*. DOE-EH-4.2.1.3-EPIcode Code Guidance, U.S. Department of Energy, Office of Environment, Safety and Health, Washington, D.C.

Draxler RR. 1999. *HYSPLIT4 User's Guide*. NOAA Tech. Memo. ERL ARL-230, NOAA Air Resources Laboratory, Silver Spring, MD.

Droppo JG. 2004. *Characterization of the Near-Field Transport and Dispersion of Vapors Released from the Headspace of Hanford Site Underground Storage Tanks*. PNNL-14767, Pacific Northwest National Laboratory, Richland, WA.

EPA. 1995. *User's Guide for the Industrial Source Complex (ISC3) Dispersion Models*. EPA-454/B-95-003a, U.S. Environmental Protection Agency, Research Triangle Park, NC.

EPA. 1999. *PCRAMMET User's Guide*. EPA-454/B-96-001, U.S. Environmental Protection Agency, Research Triangle Park, NC.

EPA. 2003. *Comparison of Regulatory Design Concentrations*. EPA-454/R-03-002, U.S. Environmental Protection Agency, Washington, D.C.

EPA. 2004a. *User's Guide for the AMS/EPA Regulatory Model – AERMOD*. EPA-454/B-03-001, U.S. Environmental Protection Agency, Research Triangle Park, NC.

EPA. 2004b. *User's Guide for the AERMOD Meteorological Preprocessor (AERMET)*. EPA-454/B-03-002. U.S. Environmental Protection Agency, Research Triangle Park, NC.

EPA. 2007. *The CAMEO® Software System, ALOHA® User's Manual*. U.S. Environmental Protection Agency, National Atmospheric Administration, Office of Response and Restoration Emergency Response Division Seattle, WA.

EPA. 2012. *Documentation of the Evaluation of CALPUFF and Other Long Range Transport Models Using Tracer Field Experiment Data*. EPA-454/R-12-003, U.S. Environmental Protection Agency, Research Triangle Park, NC.

Glantz CS, KJ Allwine, MA Pelton, and KJ Pattison. 2002. *User's Guide for the Air Pollutant Graphical Environmental Modeling System (APGEMS)*. PNNL-14043, Pacific Northwest National Laboratory, Richland, WA.

Hoitink, DJ, KW Burk, JV Ramsdell, Jr., and WJ Shaw. 2005. *Hanford Site Climatological Summary 2004 with Historical Data*. PNNL-15160, Pacific Northwest National Laboratory, Richland, WA.

Huckaby JL, LA Mahoney, JG Droppo, and JE Meacham. 2004. *Overview of Hanford Site High-Level Waste Tank Gas and Vapor Dynamics*. PNNL-14831, Pacific Northwest National Laboratory, Richland, WA.

Huckaby JL, KB Olsen, DS Sklarew, JC Evans, KM Remund. 1997. *Measurements of Waste Tank Passive Ventilation Rates Using Tracer Gases*. PNNL-11683, Pacific Northwest National Laboratory, Richland, WA.

Leone JM, JS Nasstrom, DM Maddix, DJ Larson, G Sugiyama, and DL Ermak. 2001. *Lagrangian Operational Dispersion Integrator (LODI) User's Guide, Version 1.0*. UCRL-AM-212798, Lawrence Livermore National Laboratory, Livermore, CA.

Lipton S and J Lynch. 1994. *Handbook of Health Hazard Control in the Chemical Process Industry*. New York: John Wiley & Sons, Inc.

Meacham JE, JO Honeyman, TJ Anderson, ML Zabel, and JL Huckaby. 2006. *Industrial Hygiene Chemical Vapor Technical Basis*. RPP-22491, Rev. 1, CH2M Hill, Richland, WA.

Nelson M and MJ Brown. 2013. *The QUIC Start Guide (v 6.01): The Quick Urban & Industrial Complex (QUIC) Dispersion Modeling System*. LA-UR-13-27291, Los Alamos, NM.

NETL. 2016. *MFiX - Open source multiphase flow modeling for real-world applications 2016-01 User Guide*. National Engineering Technology Laboratory, Pittsburgh, PA.

NIST. 2017. *Fire Dynamics Simulator User's Guide*. National Institute of Standards and Technology, NIST Special Publication 1019, Sixth Edition, Gaithersburg, MD.

NRC. 1997. *Atmospheric Relative Concentrations in Building Wakes*, NUREG/CR-6331, Rev. 1, U.S. Nuclear Regulatory Commission, Washington, D.C.

Pasquill F. 1961. "The Estimation of the Dispersion of Windborne Material." *Meteorological Magazine* 90(1063):33-49.

Rishel JP and CS Glantz. 2008. "DUSTRAN – An Atmospheric Dispersion Model for Consequence Assessment Applications in Emergency Operations Centers." In *2nd International Joint Topical Meeting on Emergency Preparedness and Response and Robotic and Remote Systems*, March 9-12, 2008, Albuquerque, New Mexico, pp. 177-181. American Nuclear Society, La Grange Park, IL.

SAFER Systems, LLC. 2015. *Operator Training Guide, Version 10.5*. PM0047-1505-IE, Westlake Village, CA.

Scire JS, DG Strimaitis, and RJ Yamartino. 2000a. *A User's Guide for the CALPUFF Dispersion Model (Version 5)*. Earth Tech, Inc., Concord, MA.

Scire JS, FR Robe, ME Fernau, and RJ Yamartino. 2000b. *A User's Guide for the CALMET Meteorological Model (Version 5)*. Earth Tech, Inc., Concord, MA.

Slade DH. 1968. *Meteorology and Atomic Energy*, Air Resource Laboratories. National Technical Information Service, U.S. Department of Commerce, TID-24190. 445 pages.

Sykes RI, SF Parker, DS Henn, CP Cerasoli, and LP Santos. 1998. *PC-SCIPUFF Version 1.2PD Technical Documentation*. ARAP Report No. 718, Titan Corporation, Titan Research & Technology Division, ARAP Group, Princeton, NJ.

Turner DB. 1994. *Workbook of Atmospheric Dispersion Estimates: An Introduction to Dispersion Modeling*, Second Edition. CRC Press, ISBN: 9781566700238. 192 pages.

Wilmarth WR, MA Maier, TW Armstrong, RL Ferry, JL Henshaw, RA Holland, MA Jayjock, MH Le, JC Rock, and C Timchalk. 2014. *Hanford Tank Vapor Assessment Report*. SRNL-RP-2014-00791, Rev. 0, Savannah River National Laboratory, Aiken, SC.

WRPS. 2015. *Implementation Plan for Hanford Tank Vapor Assessment Report Recommendation*. Washington River Protection Solutions, Richland, WA.

Appendix A

Plume Model Detailed Summary Tables

Appendix A - Plume Model Detailed Summary Tables

Table A.1. AERMOD Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>AERMOD (AMS/EPA Regulatory Model)</p> <p>AERMOD is a steady-state plume model that incorporates state-of-the science planetary boundary layer theory on turbulence structure and scaling concepts, including treatment of both surface and elevated sources within building wakes, in both simple and complex terrain.</p> <p>AERMOD provides estimates of both air concentration and ground deposition (wet and/or dry).</p>
2	Model Developer	American Meteorological Society (AMS)/U.S. Environmental Protection Agency (EPA)
3	Availability	<p>AERMOD is freely available from the EPA’s SCRAM website (https://www3.epa.gov/ttn/scram/dispersion_prefrec.htm#aermod); the model is run from a Windows command prompt.</p> <p>AERMOD is also available through commercial vendors (e.g., http://weblakes.com/; http://breeze-software.com/) with a graphical user interface.</p>
4	Model Description	<p>AERMOD is a steady-state, Gaussian plume model. In the stable boundary layer (SBL), it assumes the concentration distribution to be Gaussian in both the vertical and horizontal direction. In the convective boundary layer (CBL), the horizontal distribution is also assumed to be Gaussian, but the vertical distribution is described with a bi-Gaussian probability density function. Additionally, in the CBL, AERMOD treats “plume lofting,” whereby a portion of plume mass, released from a buoyant source, rises to and remains near the top of the boundary layer before becoming mixed into the CBL. AERMOD also tracks any plume mass that penetrates into the elevated stable layer, and then allows it to re-enter the boundary layer when and if appropriate. For sources in both the CBL and the SBL, AERMOD treats the enhancement of lateral dispersion resulting from plume meander.</p> <p>Using a relatively simple approach, AERMOD incorporates current concepts about flow and dispersion in complex terrain. Where appropriate, the plume is modeled as either impacting and/or following the terrain. This approach has been designed to be physically realistic and simple to implement while avoiding the need to distinguish among simple, intermediate and complex terrain, as required by other regulatory models. As a result, AERMOD removes the need for defining complex terrain regimes. All terrain is handled in a consistent and continuous manner while considering the dividing streamline concept in stably stratified conditions.</p> <p>AERMOD characterizes the PBL through both surface and mixed layer scaling by constructing vertical profiles of required meteorological variables based on measurements and extrapolations of those measurements using similarity (scaling) relationships. Vertical profiles of wind speed, wind direction, turbulence, temperature, and temperature gradient are estimated using all available meteorological observations. AERMOD is designed to run with a minimum of observed meteorological parameters. AERMOD can operate using data of a type that is readily available from National Weather Service (NWS) stations, and requires only a single surface measurement of wind speed, wind direction, and ambient temperature. AERMOD also needs observed cloud cover. However, if cloud cover is not available (e.g., from an on-site monitoring</p>

Table A.1 (cont.)

Id	Parameter	Description
		<p>program), two vertical measurements of temperature (typically at 2 and 10 m), and a measurement of solar radiation can be substituted. A full morning upper air sounding (RAWINSONDE) is required in order to calculate the convective mixing height throughout the day. Surface characteristics (surface roughness, Bowen ratio, and albedo) are also needed in order to construct similarity profiles of the relevant PBL parameters.</p> <p>The AERMOD modeling system consists of two pre-processors and the AERMOD dispersion model; the pre-processors are separate programs that must be run before running AERMOD.</p> <p>The meteorological preprocessor (AERMET) provides AERMOD with the meteorological information it needs to characterize the PBL. AERMET uses standard meteorological data and surface characteristics to calculate boundary layer parameters (e.g., mixing height, friction velocity, etc.) needed by AERMOD. This data, whether measured off-site or on-site, must be representative of the meteorology in the modeling domain.</p> <p>The terrain pre-processor, called AERMAP, is used to characterize terrain for discrete receptors and receptor grids in AERMOD. AERMAP uses a gridded terrain data file called a Digital Elevation Model (DEM) for the modeling domain to calculate a representative terrain-influence height (i.e., hill-height scale) associated with each receptor location. The gridded data is supplied to AERMAP in the format of the DEM data. The terrain preprocessor can also be used to compute elevations for sources.</p>
5	Intended Application(s)	<p>AERMOD is intended to be used for regulatory modeling applications. The model is listed in 40 CFR Part 51, Appendix W, and is required to be used for State Implementation Plan (SIP) revisions for existing sources and for New Source Review (NSR) and Prevention of Significant Deterioration (PSD) programs.</p> <p>AERMOD can also be used in general engineering applications, such as the determination of good engineering practice stack heights.</p>
6	Strengths and Weaknesses	<p>Strengths:</p> <ul style="list-style-type: none"> • AERMOD is a well-documented, tested model that was developed by the EPA specifically for regulatory modeling applications. AERMOD uses state-of-the-science boundary layer theory to estimate air concentrations downwind of a source. <p>Weaknesses:</p> <ul style="list-style-type: none"> • AERMOD is intended to model continuous sources, with defined hourly emission rates. Because AERMOD is a plume model, the plume is assumed to extend infinitely downwind of the source. • AERMOD estimates average (i.e., 1-hour or greater) concentrations, not peak concentrations. Therefore, its use should be limited to applications that require average concentrations, such as regulatory modeling and/or research.

Table A.1 (cont.)

Id	Parameter	Description
7	Model Inputs	<p>Source:</p> <ul style="list-style-type: none"> • Point: emission rate, gas exit temperature, inside stack diameter, gas exit velocity, gas exit flow rate • Area: emission rate, length, width, orientation angle from true north, initial vertical dimension • Volume: emission rate, length of side, initial lateral dimension, initial vertical dimension • Line: emission rate, length, width, initial vertical dimension <p>Building Types (for downwash): rectangular, circular, polygonal</p> <p>Receptor Types: discrete, Cartesian, and/or polar</p> <p>Meteorology: surface and twice-daily upper air soundings (required); onsite tower data (optional)</p> <ul style="list-style-type: none"> • Surface data: wind speed, wind direction, temperature, dew-point temperature, relative humidity, sea-level pressure, precipitation amount, precipitation type, ceiling height, sky cover • Twice-daily soundings: vertical profile of wind speed, wind direction, temperature, and dew-point temperature • Onsite tower data: multiple levels of temperature, dew-point temperature, wind direction, wind speed, standard deviation of the vertical/horizontal wind
8	Model Outputs	Tabular outputs of hourly averages or other user-defined averaging periods for the defined receptors. User can specify the output of various “highest” values (1 st , 2 nd , 3 rd , etc.) for each receptor location, for a given averaging period.
9	Model Validation	A total of 17 databases were used in the evaluation of AERMOD, which included various combinations of flat or elevated terrain, building downwash or non-building downwash, rural or urban conditions (see AERMOD model evaluation paper, EPA-454/R-03-003).
10	Runtime Characteristics	Varies depending on the number of sources and receptors, but generally a few seconds for each hourly time step.
11	Computer Platform	Windows
12	Reference Document(s)	EPA. 2004. <i>User’s Guide for the AMS/EPA Regulatory Model – AERMOD</i> . EPA-454/B-03-001. Research Triangle Park, NC.

Table A.2. ISC Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>ISC (Industrial Source Complex) (EPA 1995)</p> <p>ISC is a straight-line, steady-state Gaussian plume model that is used to model industrial-type sources emissions, such as stacks and vents (point sources), storage piles (area sources), and conveyor belts or roads (line sources). ISC includes methods for accounting for plume rise, building downwash, terrain, and deposition (both wet and dry).</p> <p>ISCST3 provides estimates of both air concentration and ground deposition (wet and/or dry) for user-selected, short-term averages (i.e., one-hour or longer) as well as long-term averages spanning the entire period of input meteorology.</p> <p>Note: On October 21, 2005, AERMOD replaced ISC as the EPA’s preferred air dispersion model in the Agency’s “Guideline on Air Quality Models” (Appendix W). Therefore, AERMOD should be used over ISC for most regulatory applications. However, ISC is considered an “alternative” model and can be used in regulatory applications with case-by-case justification to the Reviewing Authority.</p>
2	Model Developer	EPA
3	Availability	<p>ISCST3 is freely available from the EPA’s SCARM website (https://www3.epa.gov/ttn/scram/dispersion_alt.htm#isc3); the model is run from a Windows command prompt.</p> <p>ISCST3 is also available through commercial vendors (e.g., http://weblakes.com/; http://breeze-software.com/) with a graphical user interface.</p>
4	Model Description	<p>ISC is a straight-line, steady-state Gaussian plume model that is used to model industrial-type sources emissions, such as stacks and vents (point sources), storage piles (area sources), and conveyor belts or roads (line sources). ISC includes methods for accounting for plume rise, building downwash, terrain, and deposition (both wet and dry).</p> <p>ISCST3 provides estimates of both air concentration and ground deposition (wet and/or dry) for user-selected, short-term averages (i.e., 1-hour or longer) as well as long-term averages spanning the entire period of input meteorology.</p> <p>Diffusion: ISCS uses two sets of diffusion coefficients for rural (Pasquill-Gifford) and urban (Briggs) dispersion. The ISC User’s Guide (EPA 1995) notes that while the Briggs functions are assumed to be valid for downwind distances less than 100 m, concentrations at receptors less than 100 m from a source may be suspect.</p> <p>Plume Rise/Building Downwash: The original ISC model contained algorithms to account for increased plume height due to buoyancy and momentum, as well as two methods for assessing building downwash. The selection of the appropriate building downwash method was made by model and depends on the building width/height dimensions with respect to the source. A separate version of ISC, called the ISC Plume Rise Model Enhancements (ISC-PRIME) model, was later developed to address known shortcomings and inconsistencies with the original ISC building downwash models.</p> <p>ISC-PRIME incorporates enhanced plume diffusion coefficients due to the turbulent wake as well as reduced plume rise caused by a combination of the descending streamlines (i.e., flow) in the lee of the building and the increased entrainment in the</p>

Table A.2 (cont.)

Id	Parameter	Description
		<p>wake. PRIME is fully integrated with ISC and calculates fields of turbulence intensity, wind speed, and the slopes of the mean streamlines as a function of the projected building dimensions. These fields gradually decay to ambient values downwind of the building. Coupled with a numerical plume rise model and these local values, PRIME determines the change in plume centerline location with downwind distance and the rate of plume dispersion. Plume rise therefore incorporates the descent of the air containing the plume material, and rise of the plume relative to the streamlines due to buoyancy or momentum effects.</p>
		<p>Deposition: In ISC, a resistance method is used to calculate a particle deposition velocity. The resistance method includes parameterizations for the effects of Brownian motion, inertial impaction, and gravitational settling. The deposition velocity is written as the inverse of a sum of resistances to pollutant transfer through various atmospheric layers, plus gravitational settling terms. The deposition of material to the ground is calculated as the product of the concentration and the deposition velocity.</p>
		<p>Terrain: ISCST3 uses different dispersion algorithms for simple, intermediate, and complex terrain; terrain determination is as follows:</p> <ul style="list-style-type: none"> • Simple Terrain: If the terrain height is less than or equal to the physical release height, then that receptor is defined as simple terrain, and the concentration is based on the simple terrain algorithm only. • Complex Terrain: If the terrain height is equal to or exceeds the plume height, then that receptor is defined as complex terrain for that hour and that source, and the concentration is based on the complex terrain screening algorithm only. • Intermediate Terrain: If the terrain height is below the plume height but exceeds the physical release height, then that receptor is defined as intermediate terrain for that hour and source. For intermediate terrain receptors, concentrations from both the simple terrain algorithm and the complex terrain algorithm are obtained and the higher of the two concentrations is used for that hour and that source.
		<p>Commercial versions of the ISC software (i.e., Lake Environmental or Trinity Consultants) provide a graphical user interface that allows users to import standard terrain files to provide elevations to model sources, building, and receptors.</p>
		<p>Meteorology: A meteorological preprocessor called PCRAMMET provides ISC with the meteorological information it needs to estimate air concentrations and ground deposition. PCRAMMET uses standard surface observations and twice-daily mixing heights to estimate the following parameters for ISC:</p> <ul style="list-style-type: none"> • hourly values of atmospheric stability class, wind speed, and wind direction • hourly mixing heights <p>optionally, parameters for dry and wet deposition</p>
5	Intended Application(s)	<p>ISC has been superseded by AERMOD for regulatory modeling applications. Therefore, ISC should only be used on an approved basis for regulatory applications or for general engineering applications, such as the determination of good engineering practice stack heights.</p>

Table A.2 (cont.)

Id	Parameter	Description
6	Strengths and Weaknesses	<p>Strengths:</p> <ul style="list-style-type: none"> • ISC is a well-documented, tested model that was developed by the EPA specifically for regulatory modeling applications; however, more recently it has been superseded by AERMOD for regulatory modeling applications. <p>Weaknesses:</p> <ul style="list-style-type: none"> • ISC intended to model continuous sources, with defined hourly emission rates. Because ISC is plume model, the plume is assumed to extend infinitely downwind of the source. • ISC provides estimates of average (i.e., 1-hour or greater) concentrations, not peak concentrations. Therefore, its use should be limited to applications that require average concentrations, such as regulatory modeling and/or research.
7	Model Inputs	<p>ISC source types, building types, and receptor types are similar to AERMOD and include:</p> <p>Source:</p> <ul style="list-style-type: none"> • Point: emission rate, gas exit temperature, inside stack diameter, gas exit velocity, gas exit flow rate • Area: emission rate, length, width, orientation angle from true north, initial vertical dimension • Volume: emission rate, length of side, initial lateral dimension, initial vertical dimension • Line: emission rate, length, width, initial vertical dimension <p>Building Types (for downwash): rectangular, circular, polygonal</p> <p>Receptor Types: discrete, Cartesian, and/or polar</p> <p>Meteorology: surface observations and twice-daily mixing height (required); surface observations include</p> <ul style="list-style-type: none"> • surface data: wind speed, wind direction, dry bulb temperature, opaque cloud cover, ceiling height, station pressure (dry deposition), and precipitation type and amount (wet deposition).
8	Model Outputs	<p>Tabular outputs of hourly averages or other user-defined averaging periods for the defined receptors. User can specify the output of various “highest” values (1st, 2nd, 3rd, etc.) for each receptor location, for a given averaging period.</p>
9	Model Validation	<p>ISCST3 has been extensively evaluated by the EPA as well as in the independent literature. With the promulgation of AERMOD as a replacement to ISCST3, a series of model comparisons were made to understand and verify consistency between the models (EPA 2003).</p> <p>ISC-PRIME contains advanced building downwash algorithms; this version of ISC was also compared to AERMOD (EPA 2003). In addition, ISC-PRIME was evaluated against 14 candidate databases, including 8 tracer experiments, 3 long-term (1-year) datasets, and 3 wind tunnel studies (EPRI 1997).</p>
10	Runtime Characteristics	<p>Varies depending on the number of sources and receptors, but generally a few seconds for each hourly time step.</p>
11	Computer Platform	<p>Windows DOS (EPA Version); Window User Interface (commercial versions)</p>

Table A.3. EPIcode Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	EPIcode (Emergency Prediction Information code) - A chemical dispersion modeling software product (Version 7.0 is a toolbox code and Version 8.0 is the latest).
2	Model Developer	Homann Associates, Inc. developed EPIcode. In 2012, LLNL/NARAC acquired the EPIcode software for use in DOE applications.
3	Availability	Version 8.0 available through LLNL and is free for anyone associated with DOE.
4	Model Description	<p>EPIcode uses the Gaussian Plume Model and does not use any “black-box” techniques. EPIcode uses virtual source terms are used to more accurately model the initial distribution of material associated with explosions or fires.</p> <p>The “puff” equation is used for an instantaneous term release, and the “continuous” equation is used for a continuous release. For a non-instantaneous term release (0.5 minutes, 10 minutes, etc.) EPIcode automatically selects the appropriate equation for each specific downwind location. This selection process is based on the plume length (release duration × wind speed) relative to the standard deviation in the horizontal axis at the specific downwind location being considered.</p> <p>The EPIcode Library contains over 2,000 chemical substances along with the associated exposure levels accepted by various professional organizations and regulatory agencies. These include all of the current American Industrial Hygiene Association Emergency Response Planning Guidelines (ERPGs), Department of Energy Temporary Emergency Exposure Limits (TEELs), and Acute Exposure Guideline Limits (AEGs).</p> <p>EPIcode is best suited for “short” duration plumes, ranging from approximately several minutes to several hours.</p> <p>The Gaussian models used in EPIcode are directly applicable to neutrally buoyant releases in which the initial chemical cloud density is approximately equal to that of the ambient air. If the density of the initial chemical cloud is greater than that of the ambient air, however, then the possibility exists for dense-gas type of atmospheric transport and dispersion. However, as atmospheric air mixes with the cloud, dilution occurs that causes dense gas transport effects to essentially become negligible as the density of the plume mixture approaches that of the ambient air. All dense gas releases, therefore, eventually transition to transport and dispersion that is characteristic of a neutrally buoyant plume.</p>
5	Intended Application(s)	<p>EPIcode provides emergency planners and response personnel with rapid modeling to estimate downwind concentrations of chemicals (gas, vapor, or aerosol) released during industrial and transportation accidents.</p> <p>EPIcode uses equations from Briggs to determine sigma-y and sigma-z (for use in its Gaussian dispersion codes).</p> <p>EPIcode is also a DOE toolbox code for use in documented safety analysis development.</p>
6	Strengths and Weaknesses	<p>Strengths:</p> <ul style="list-style-type: none"> • Version 7 is a DOE Toolbox code. • Is easy to use and runs are executed quickly. • Output can be in terms of tables or contour maps. • Can be run in a manner where X/Q value can be obtained. • Enables complex geometry to model non-point source and elevated release.

Table A.3 (cont.)

Id	Parameter	Description
		<ul style="list-style-type: none"> • Enables the modeling of a buoyant plume from hotter than air sources. • Enables inputting deposition velocity. • Enables accounting for plume meander. • Fast and simple to use. • Every time DOE updates the PACS, LLNL updates the database and posts it on their website. • By using a virtual source term with initial horizontal and vertical plume sizes, mimics wake effects. • Has a special Stability Class G correction.
		<p>Weaknesses:</p> <ul style="list-style-type: none"> • Does not account for building wake effects. • Does not contain special algorithms for near-field dispersion. • Does not model time variant puff releases. • With Version 7 and 8 cannot input met files enabling an analysis based on local met patterns. The EPIcode developer is working on an update that would allow use of met files for dispersion analysis.
7	Model Inputs	<p>EPIcode has the following basic input areas: dispersion model type, source term, meteorology, receptor, and setup.</p> <p>Model Type: Only short-term and continuous are germane to the vapor program. EPIcode also includes ability to model spills, fires, and explosions.</p> <p>Source Term:</p> <ul style="list-style-type: none"> • Substance • Units • Total released, units, and release duration (if term release model) • Release rate and units (if continuous release model) • Effective release height • Deposition velocity • Airborne release fraction • Parameters for buoyant plume rise from heat (if selected) <p>Meteorology: wind speed and stability class</p> <p>Receptor: receptor locations and receptor height (up to 20)</p> <p>Setup</p> <ul style="list-style-type: none"> • Terrain (or surface roughness value) • Enabling of inversion and ceiling height • Sampling time for plume meander • Height at which wind speed was measured
8	Model Outputs	<p>Provides options for table or figure outputs with contour lines. Note with versions 7 and 8 the user can run EPIcode to develop X/Q. This is accomplished by using the Append QA option on the output tab.</p>
9	Model Validation	<p>Standard DOE Software Quality Assurance measures are required. EPIcode provides standard runs to ensure that it is running appropriately on the given system. By clicking EPIcode QC, it will run standard runs that check the program. There are 6 cases.</p> <p>Because EPIcode V7 is a toolbox code, commercial grade dedication would not be required. LLNL is currently in the process of getting V8 to become a toolbox code.</p>

Table A.3 (cont.)

Id	Parameter	Description
10	Runtime Characteristics	The process of inputting data into EPIcode is fast. The execution of EPIcode is also fast (on the order of seconds).
11	Computer Platform	Versions 7 and 8 run on Windows 7, 8, 10.
12	Reference Document(s)	<p>EPIcode provides an extensive help system that comes with every installation.</p> <p>There is a DRAFT EPIcode User Manual for Version 8.</p> <p>DOE-EH-4.2.1.3-EPIcode Code Guidance, <i>EPIcode Computer Code Application Guidance for Documented Safety Analysis - Final Report</i>, 2004, U.S. Department of Energy Office of Environment, Safety and Health 1000 Independence Ave., S.W. Washington, D.C. 20585-2040.</p> <p>Thoman DC, KR O’Kula, JC Laul, MW Davis, and KD Knecht. 2006. “Comparison of ALOHA and EPIcode for Safety Analysis Applications,” <i>Journal of Chemical Health & Safety</i> 13(6), November/December 2006.</p>

Table A.4. ALOHA Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>ALOHA (Areal Locations of Hazardous Atmospheres) is a computer program designed to model chemical releases for emergency responders and planners. It can estimate how a toxic cloud might disperse after a chemical release—as well as several fires and explosions scenarios. Version 5.4.6 is the latest.</p> <p>ALOHA is designed to produce reasonable results quickly enough to be of use to responders during a real emergency. Therefore, ALOHA’s calculations represent a compromise between accuracy and speed. Many of ALOHA’s features were developed to quickly assist the responder.</p>
2	Model Developer	<p>ALOHA is part of the CAMEO® software suite, which is developed jointly by the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Environmental Protection Agency (EPA).</p>
3	Availability	<p>Available for free through the following link: http://www2.epa.gov/cameo/aloha-software</p>
4	Model Description	<p>ALOHA was designed with first responders in mind. Its air dispersion model is intended to be used to estimate the areas near a short-duration chemical release where key hazards—toxicity, flammability, thermal radiation, or overpressure—may exceed user-specified Levels of Concern (LOCs). ALOHA is not intended for use with radioactive chemical releases, nor is ALOHA intended to be used for permitting of stack gas or modeling chronic, low-level (“fugitive”) emissions. Other models are designed to address larger scale and/or air quality issues (Turner and Bender 1986). Since most first responders do not have dispersion modeling backgrounds, ALOHA has been designed to require input data that are either easily obtained or estimated at the scene of an accident. ALOHA’s user interface helps in choosing inputs.</p> <p>ALOHA uses the Gaussian model to predict how gases that are about as buoyant as air will disperse in the atmosphere. Such neutrally buoyant gases have about the same density as air. User can select a Gaussian or heavy gas model or let ALOHA automatically choose (where it bases this choice mainly on molecular weight, size of the release, and temperature of the gas cloud).</p> <p>In an ALOHA scenario, the <i>source</i> is the vessel or pool from which a hazardous chemical is released. The <i>source strength</i> is the rate at which the chemical enters the atmosphere or the burn rate, depending on the scenario.</p> <p>ALOHA can model four types of sources:</p> <ul style="list-style-type: none"> • Direct: chemical release directly into the atmosphere (using user-determined rate/amount and bypassing ALOHA’s source calculations) • Puddle: chemical has formed a liquid pool • Tank: chemical is escaping from a storage tank • Gas Pipeline: chemical is escaping from a ruptured gas pipeline <p>For each source, ALOHA will allow the user to choose the scenario with only toxic vapor cloud option germane to the vapor program.</p> <p>ALOHA allows the option of outputting the threat at a given downwind point (x, y) as a function of time or a threat zone (distance for given concentrations of concern).</p>

Table A.4 (cont.)

Id	Parameter	Description
5	Intended Application(s)	Developed as a tool for emergency response and emergency preparedness/planning. It is also widely used throughout the DOE complex to support nuclear safety applications.
6	Strengths and Weaknesses	<p>Strengths</p> <ul style="list-style-type: none"> • Both the inputting of data and file execution are relatively fast. • Minimizes data entry errors by cross-checking the input values and warning the user if the value is unlikely or not physically possible. • ALOHA contains extensive help associated with the various program input fields. • Enables modeling of elevated releases. <p>Weaknesses</p> <ul style="list-style-type: none"> • Does not model time-variant puff releases. • Results are less reliable for conditions of low wind speed or very stable atmospheric conditions. • Does not provide X/Q values. • Does not model plume buoyancy from hotter than ambient plumes. • Does not model dispersion using site specific met data files. • Does not model wake effects. • Users are told to use caution in interpreting results with very low wind speeds and/or very stable atmospheric conditions. • Does not model plume meander. • Does not model deposition.
7	Model Inputs	<p>A series of dialog boxes prompt users to enter information about the scenario (e.g., chemical, weather conditions, and the type of release).</p> <p>User inputs the following general information:</p> <ul style="list-style-type: none"> • Site data: city, type of building, and type of environment. • Chemical data: either from its database or add a custom one. • Atmospheric Conditions: wind speed and direction from, air temperature, stability class, inversion height, cloud cover, humidity level. Note: this option also is where the user inputs info on surface roughness. • Source Info: can select instantaneous or continuous release source. User inputs units, amount or rate, release height.
8	Model Outputs	Provides both a text and graph of distance for three threat areas (based on concentrations of concern). Also, has the option for providing the threat (concentration) at a given location (x and y) as a function of time.
9	Model Validation	Did not find that test cases (for ensuring ALOHA runs properly on a given system) are provided as part of the package.
10	Runtime Characteristics	Both the inputting of data and execution of runs is very fast.
11	Computer Platform	The Windows version can be run on Windows 7, Windows 8, Windows 8.1, and Windows 10 operating systems.

Table A.4 (cont.)

Id	Parameter	Description
12	Reference Document(s)	<p>The CAMEO[®] Software System, ALOHA[®] User's Manual, February 2007, Environmental Protection Agency, Washington D.C., National Atmospheric Administration, Office of Response and Restoration Emergency Response Division Seattle, Washington.</p> <p>NOAA's National Ocean Service • Office of Response and Restoration, ALOHA fact sheet, which can be downloaded off of the following link: http://response.restoration.noaa.gov/sites/default/files/aloha.pdf.</p> <p>DOE-EH-4.2.1.3-ALOHA-Gap Analysis, <i>Software Quality Assurance Improvement Plan: ALOHA Gap Analysis</i>, May 2004. (Covers version 5.2.3 ~ where version 5.4.6 is the latest).</p> <p>DOE-EH-4.2.1.4-ALOHA-Code Guidance, <i>ALOHA Computer Code Application Guidance for Documented Safety Analysis</i>, June 2004. (Covers version 5.2.3 ~ where version 5.4.6 is the latest).</p> <p>Thoman DC, KR O'Kula JC Laul, MW Davis, and KD Knecht. "Comparison of ALOHA and EPIcode for Safety Analysis Applications," <i>Journal of Chemical Health & Safety</i>, Volume 13, Number 6, November/December 2006.</p>

Table A.5. ARCON96 Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	ARCON96 (Atmospheric Relative Concentrations in Building Wakes computer code) is a model for calculating concentrations near buildings. It is used by the U.S. Nuclear Regulatory Commission (NRC) to assess nuclear power plant control room habitability under accident conditions. ARCON96 uses hourly averaged meteorological data and recently developed methods for estimating dispersion near buildings to calculate relative concentrations (X/Q) at control room air intakes that would be exceeded no more than 5% of the time. Relative concentrations are calculated for averaging periods ranging from 1 hour to 30 days duration to support control room habitability dose calculations.
2	Model Developer	NRC/Pacific Northwest National Laboratory (PNNL)
3	Availability	Available through Oak Ridge - RSICC. Is free upon justified need.
4	Model Description	ARCON96 is a model for calculating concentrations in the vicinity of buildings. It is used by the NRC to assess nuclear power plant control room habitability under accident conditions. ARCON96 uses hourly averaged meteorological data and recently developed methods for estimating dispersion near buildings to calculate relative concentrations (X/Q) at control room air intakes that would be exceeded no more than 5% of the time. Relative concentrations are calculated for averaging periods ranging from 1 hour to 30 days duration to support control room habitability dose calculations.

The basic diffusion model implemented in the ARCON96 code is a straight-line Gaussian plume model that assumes the release rate is constant for the entire period of release. This assumption is made to permit evaluation of potential effects of accidental releases without having to specify a complete release sequence.

ARCON96 permits evaluation of ground-level, vent, and elevated releases. Building wake effects are considered in evaluation of relative concentrations from ground-level releases. Vent releases are treated as a mixed ground-level and elevated release. The proportions of the mixture are determined by the ratio between the effluent vertical velocity and the release-height wind speed.

Elevated releases are treated in the usual manner with correction for downwash and differences in terrain elevation between the stack and the control room intake.

ARCON96 calculates relative concentrations using hourly meteorological data. It then combines the hourly averages to estimate concentrations for periods ranging in duration from 2 hours to 30 days. Wind direction is considered as the averages are formed. As a result, the averages account for persistence in both diffusion conditions and wind direction. Cumulative frequency distributions are prepared from the average relative concentrations. Relative concentrations that are exceeded no more than 5% of the time (95th percentile relative concentrations) are determined from the cumulative frequency distributions for each averaging period. Finally, the relative concentrations for five standard averaging periods used in control room habitability assessments are calculated from the 95th percentile relative concentrations.

ARCON96 permits users to simulate releases from area sources as well as point sources. Centerline concentrations are used up to the first 8 hours in each time period average and sector-average concentrations are used for the remaining hours in longer-term averages.

Table A.5 (cont.)

Id	Parameter	Description
5	Intended Application(s)	ARCON96 was developed for calculating airborne concentrations near control rooms. Therefore, the code is useful for estimating design concentrations in the near-field (i.e., within a few hundred meters of the release).
6	Strengths and Weaknesses	<p>Strengths:</p> <ul style="list-style-type: none"> • ARCON96 is endorsed by the NRC for application to calculate more realistic X/Q values in the near-field. The short-distance use is justified by the code's empirically-derived horizontal and vertical turbulence magnitudes, which provide a more accurate match for a variety of wind tunnel studies and field tracer experiments. Meets NRC criteria for receptor distances as near as 10 m from the release. • Has a unique low wind speed correction algorithm. • Models buoyant plumes. • Takes into account building wake effects. • Takes into account plume meander. • Allows for stack releases. <p>Weaknesses:</p> <ul style="list-style-type: none"> • Uses a straight-line Gaussian diffusion model that does not allow for temporal and spatial variations in the wind field. • Assumes a constant release rate for an entire 30-day period, not allowing for variations in release rates. • Does not model time-variant puff releases. • Only runs on Windows XP or earlier versions. Has not been updated to run on recent windows versions. • Relatively not as simple to run as other codes.
7	Model Inputs	<p>The user inputs meteorological information, source data, and receptor data.</p> <ul style="list-style-type: none"> • Meteorological input: number of data files; upper- and lower-level measurement heights; wind speed. • Source input: release type (i.e., ground, vent, stack); release height; building area; stack flow, vertical velocity and stack radius. • Receptor input: distance to receptor (e.g., control room intake); intake height; source-receptor elevation difference; direction from receptor to source.
8	Model Outputs	<p>Relative concentration (X/Q) values at 95th percentile for each time period.</p> <p>Hourly value range (maximum and minimum) of centerline and sector-average X/Q values.</p> <p>Table of cumulative frequency distributions of X/Q values.</p>
9	Model Validation	Code was developed and tested in accordance with the requirements of ANSI/ASME NQA-1, 1986 edition (QA Requirements for Nuclear Facilities).
10	Runtime Characteristics	<p>Relatively rapid setup (on the order of minutes).</p> <p>Execution of a run takes from about ½ to 1 minute.</p>
11	Computer Platform	Only operates on Windows XP or earlier versions. It requires a Visual Basic shell under the DOS operating system.

Table A.5 (cont.)

Id	Parameter	Description
12	Reference Document(s)	<p>NRSD-2015-TD01, <i>Technical Report for Calculations of Atmospheric Dispersion at Onsite Locations for Department of Energy Nuclear Facilities</i>, Office of Nuclear Safety, U.S. Department of Energy, Washington D.C.</p> <p>NUREG/CR-6331, Rev 1, <i>Atmospheric Relative Concentrations in Building Wakes</i>, U.S. Nuclear Regulatory Commission., Washington D.C.</p> <p>Ramsdell JV, Jr. 1988. <i>Atmospheric Diffusion for Control Room Air Habitability Assessment</i>, NUREG/CR-5055, U.S. Nuclear Regulatory Commission, Washington, D.C.</p> <p>Ramsdell JV Jr. 1990. "Diffusion in Building Wakes for Ground-Level Releases." <i>Atmospheric Environment</i> 24B:377-388.</p> <p>Ramsdell JV, Jr., and CJ Fostmire. 1995. <i>Atmospheric Dispersion Estimates in the Vicinity of Buildings</i>. PNL-10286 Pacific Northwest Laboratory, Richland, Washington.</p> <p>Ramsdell JV, Jr. 1991. <i>EXTRAN: A Computer Code for Estimating Concentrations of Toxic Substances at Control Room Air Intakes</i>, NUREG/CR-5656, U.S. Nuclear Regulatory Commission, Washington, D.C.</p>

Table A.6. SAFER Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>SAFER Real-Time</p> <p>SAFER Real-Time is a suite of emergency management tools for decision-making at industrial facilities. It includes data acquisition, data display, source identification modeling, sensor response modeling, and plume modeling.</p>
2	Model Developer	SAFER Systems, LLC
3	Availability	Commercial product, http://www.safersystem.com/
4	Model Description	<p>SAFER Real-Time is an emergency response and emergency planning tool that is focused on providing information for industrial facilities to respond to chemical releases. The main elements include a screen for viewing sensor data (gas concentrations, meteorology, etc.), an alarming capability, source terms, and modeling.</p> <p>There are three main types of modeling that the code performs. First, it has a standing plume modeling tool that uses a puff for releases with durations less than 100 seconds, and a plume for releases greater than 100 seconds. Second, it has a Source Area Locator tool that estimates the most likely release position based on sensor data. Finally, it has an Advanced Back Calculation tool that estimates the release rate based on sensor data. In addition, it has a basic infiltration tool that estimates the indoor contaminant concentration based on a bulk air exchange rate. This tool also allows users to view the time series plot of concentration at a given outdoor receptor location.</p> <p>The model has a chemical library, which allows it to account for explosive releases as well as dense gas releases.</p> <p>The software is meant to run on a workstation in a control room to monitor systems in a facility. In Idle mode, the software uses wind data to provide a constantly updated quick response corridor, which is a wedge positioned downwind of a selected potential release location, with a wedge angle defined by the atmospheric stability class.</p>
5	Intended Application(s)	Emergency response tool for industrial facilities. Tracking alarms on sensors located throughout a facility.
6	Strengths and Weaknesses	<p>One of the primary strengths of the SAFER software is that it is set up to be run continuously on a workstation, allowing staff to monitor the sensor data, be notified of any alarms, and log data from a network of sensors.</p> <p>The modeling the SAFER performs is relatively basic; however, it does contain a fairly exhaustive list of chemical properties for sources common in chemical industries.</p> <p>A big weakness at the moment is that the modeling documentation is not comprehensive, so the theory behind the model(s) must be gleaned from various individual sources rather than a single User's Guide or Theory Guide. It doesn't appear that the dispersion modeling itself is particularly sophisticated. It is meant to be simple and run quickly for emergency response.</p> <p>In our experience, it appears that the model also experiences challenges in identifying source positions when the source strength is low. The Source Area Locator (SAL) appears to position the source in the correct upwind corridor, but the distance is much farther than necessary.</p>

Table A.6 (cont.)

Id	Parameter	Description
7	Model Inputs	<p>The initial setup of the SAFER Real-Time software includes integration of available sensors, including chemical sensors and meteorological sensors. SAFER has already established a business relationship with some vendors, which makes sensor integration easier; however, a variety of data streams may be integrated.</p> <p>Typical operations have the software running continuously, collecting sensor data 24/7. When a release is suspected or verified, a combination of sensor data and users input are used to model the plume.</p>
8	Model Outputs	<p>Each model run, when performed under the “Emergency Response” umbrella in the SAFER menu tree, is saved to the software database. Users may output map results as well as reports for each model run.</p> <p>The Source Area Locator result is essentially a position in space. A map showing that position, as well as a report that includes the latitude and longitude of that position, along with the sensor data that were used to compute the position is available.</p> <p>The Advanced Back Trajectory may utilize either the source position as defined by the Source Area Locator, or a user-defined source position. The model produces a source strength based on measured sensor concentration, and creates a plume. Again, the output for this is a map showing the source position and plume with the option of labeling the source position with the release rate, as well as a report that includes a graphic of the plume, source position, source strength, and sensor data.</p>
9	Model Validation	<p>Source area locator validated against liquefied natural gas release from the 1980 BURRO Experiments. Various stability class and wind speed cases were considered.</p> <p>Koopman R. P., Baker J., Cederwall R. T., Goldwire H. C., Hogan W. J. LLNL/NWC (Lawrence Livermore National Laboratory/Naval Weapons Center) 1980 LNG (Liquefied Natural Gas) Spill Tests. Burro Series Data Report.</p> <p>Goldiwire H. C., Baker J., Koopman R. P., Cederwall R. T., Hogan W. J. LLNL/NWC (Lawrence Livermore National Laboratory/Naval Weapons Center) 1980 LNG (Liquefied Natural Gas) Spill Tests. Burro Series Data Report: The Appendices.</p> <p>The back calculation model was evaluated with the Desert Tortoise tests at Frenchman Flats, NV in 1983.</p> <p>Goldwire, H.C., G. McRae, G.W. Johnson, D.L. Hipple, R.P. Koopman, J.W. McClure, L.K. Morris, R.T. Cederwall, “Desert Tortoise Seris Data Report, Pressurized Ammonia Spills,” Lawrence Livermore National Laboratory, December 1985.</p> <p>Other studies are referenced generally, but no explicit evaluations are described.</p>
10	Runtime Characteristics	Generally runs within a few minutes
11	Computer Platform	Windows or Mac

Table A.6 (cont.)

Id	Parameter	Description
12	Reference Document(s)	<p>SAFER Realtime Help File</p> <p>Khajeh Najafi S and E Gilbert. 2009. <i>User of Real-time Measurements for Estimating Release Rate</i>. (Advanced Back Calculation Paper.pdf)</p> <p>Khajehnajafi S and A Meel. 2013. "A Hybrid Model for Characterizing the Source of Hazardous Material Release. American Institute of Chemical Engineers." 9th Global Congress on Process Safety. San Antonio, TX. (AIChE-GCPS_2013-Manuscript.pdf)</p>

Table A.7. American Industrial Hygiene Association Near- and Mid- Field Plume Model Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>American Industrial Hygiene Association (AIHA) Near- and Mid- Field Plume model.</p> <p>The AIHA Near- and Mid-Field plume model formulations use a single dispersion coefficient based on PG stability class “C” (slightly unstable) to represent both horizontal and vertical diffusion for near (0-3 m) and mid (3-100 m) field distances.</p> <p>The AIHA Near- and Mid-Field plume model provides estimates of air concentration at near (0-3 m) and mid (3-100 m) field downwind distances.</p>
2	Model Developer	American Industrial Hygiene Association (AIHA)
3	Availability	<p>The AIHA-Eddy model is freely available from their website: https://www.aiha.org/get-involved/VolunteerGroups/Documents/IHMOD_Korean-AIHA-MathModel209.xls</p> <p>WRPS IH used version 9 through 2016, and has recently upgraded to version 12.</p> <p>The AIHA Near-and Mid-Field plume models operate as a macro from within Microsoft Excel; there are two formulations provided—for near (0-3 m) and mid (3-100) field applications.</p>
4	Model Description	<p>The AIHA Near- and Mid-Field plume model formulations use a single dispersion coefficient based on PG stability class “C” (slightly unstable) to represent both horizontal and vertical diffusion at near (0-3 m) and mid (3-100 m) field distances. As such, there is no mechanism to account for other or more conservative (e.g., highly stable) stability classes. Although the AIHA documentation cites “near” and “mid” field formulations, this distinction is somewhat arbitrary and misleading because the formulations are based on the PG parameterization where no such distinction is made at these distances (i.e., less than 100 m). AIHA concentrations are evaluated only for the plume centerline, directly downwind from the source. The AIHA Near-and Mid-Field plume models do not account for effects of plume rise, downwash/building wake, or terrain on pollutant concentrations downwind from a source.</p>
5	Intended Application(s)	<p>The AIHA Near- and Far-Field plume models are intended to be used for continuous releases to estimate downwind air concentrations on the plume centerline immediately downwind of the source. Two plume formulations are provide—for near (0-3 m) and mid (3-100 m) applications. Caution should be exercised when using P-G dispersion models at distance less than 100 m distances, as the experiments that were used to derive the dispersion coefficients were never validated at these short distances. Finally, it is likely other factors, such as source size and possible wake effects, are important factors to consider at these short distances.</p>

Table A.7 (cont.)

Id	Parameter	Description
6	Strengths and Weaknesses	<p>Strengths:</p> <ul style="list-style-type: none"> • The models are conceptually simple, quick, and easy to use. • The model and can be used to estimate concentration downwind of a continuous source. <p>Weaknesses:</p> <ul style="list-style-type: none"> • The diffusion is based only on Pasquill-Gifford (P-G) stability class “C”. As such, there is no mechanism to account for other or more conservative (e.g., highly stable) stability classes. • Although the AIHA documentation cites “near” and “mid” field formulations, this distinction is somewhat arbitrary and misleading because the formulations are based on the PG parameterization where no such distinction is made at these distances (i.e., less than 100 m). • Review of the mid-field (3-100 m) formulation indicates that it incorrectly uses the diffusion exponent for the far-field (greater than 100 m) formulation from the cited literature (Lipton and Lynch, 1994). The mid-field concentrations are lower than the result using the correct equation from the literature. Concentrations are about 2% lower at 3 m, and about 36% lower at 100 m. • The formulations do not account for other factors, such as source size and possible wake effects, which are important factors to consider at very short transport distances. • The formulations do not account for effects of plume rise, downwash/building wake, or terrain on pollutant concentrations downwind from a source.

Appendix B

Puff Model Detailed Summary Tables

Appendix B - Puff Model Detailed Summary Tables

Table B.1. APGEMS Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	The Air Pollutant Graphical Environmental Monitoring System (APGEMS) Version 2.0.4 is a state-of-the-art atmospheric dispersion and dose assessment model developed for emergency planning, preparedness, and response applications. It is the primary atmospheric dispersion and dose assessment modeling tool at the Emergency Operations Center at Hanford.
2	Model Developer	Pacific Northwest National Laboratory (PNNL), Primary Point of Contact: Cliff Glantz
3	Availability	Free through PNNL.
4	Model Description	APGEMS is a PC-based tool. Its modular design allows its various components to be upgraded and replaced when appropriate. The model balances the competing needs for technical precision, speedy performance, and simplicity of use. APGEMS can be used for areas with relatively uniform terrain or complex terrain environments. Source-to-receptor transport distances can range from as little as one hundred meters to a few hundred kilometers.

APGEMS uses a three-dimensional diagnostic wind model to compute the vertical and horizontal spatial variation in winds at each time step in the simulation. The wind field is determined by applying a mass-conserving interpolation technique to the surface- and upper-air observations supplied to the model. The model accounts for flow channeling, blocking by major terrain features, and drainage flows. APGEMS employs a Gaussian puff formulation to mathematically describe the concentration distribution of the released materials as they move in the mean wind field. Mathematical reflections of the concentration distribution from the ground and the top of a mixed layer modify the initial Gaussian distribution. The model treats wet and dry deposition, radioactive decay, and first-order chemical transformations of the released material.

For emergency response operations APGEMS can be run in three different modes: Standard, Exercise, and Exercise Generation. The Standard mode is used during an actual emergency or drills that involve using real-time data. The Exercise mode is used during drills that involve “canned” meteorological data. The Exercise Generation mode is used to create the comprehensive exercise data packages (including field team monitoring readings) that are used by exercise controllers to run a training event.

The model can be used for areas with relatively uniform terrain or complex terrain environments. Two nested grids are used to cover the modeling domain. A fine-resolution grid resolves the dispersion within a few kilometers of the release location and a course-resolution grid captures pollutant transport out to the limits of the modeling domain. Source-to-receptor transport distances can range from as little as one hundred meters to a few hundred kilometers.

Instructions for running an APGEMS simulation are provided using a user-friendly graphical interface. The model accesses data files that provide information on terrain, meteorology, pollutant characteristics, and other parameters. Output products are displayed using a graphical user interface. Among the products that can be displayed graphically or numerically are the distributions and cumulative exposures at ground level; time-averaged pollutant concentrations; deposition fields; total effective dose equivalent; and maximum organ dose. The values of key parameters can be viewed for each major time step in the simulation.

Table B.1 (cont.)

Id	Parameter	Description
		<p>The APGEMS modeling engine consists of three main computer programs, named TER, MET, and TDM. TER uses a base terrain file (typically a USGS digital elevation model in latitude-longitude coordinates) for the region of interest and produces disk files of gridded spatially-averaged terrain statistics (e.g., heights, drainage direction) in Universal Transversal Mercator coordinates (the primary coordinate system of APGEMS) for use by the MET and TDM programs.</p> <p>MET produces wind fields, gridded mixing heights, stabilities, and precipitation categories, using upper-air and surface weather observations. The meteorological data required by MET can be specified at variable time increments over variable periods for a variable number of stations. That is, MET can accommodate meteorological data with missing records and different averaging times. During the routine assessment mode, MET will interpolate or average data according to user-selected modeling time step (5, 10, 15, 30, or 60 minutes). Surface data will be interpolated for up to 8-hour separations in observations, and upper-air data will be interpolated for up to 12-hour separations. Surface stations with data gaps larger than 8 hours (or 12 hours for an upper-air station) will not be used during the period of the gap. The three-dimensional wind field produced by MET is described analytically, for each model time step, on up to nine terrain-following surfaces that are between the ground and a user-specified upper boundary. The two-dimensional boundary layer parameter fields (horizontal atmospheric stability categories, vertical atmospheric stability categories, mixing heights, and precipitation categories), produced by MET for each time step, are derived by interpolating the surface-station data to a 10 × 10 grid using an inverse-distance-squared weighting approach. The three-dimensional wind field is initially determined at each model time step by applying a mass-conserving interpolation technique to upper-air and surface-wind observations. The wind field is then subject to modification. For example, the model sets the surface winds to the local downslope direction to approximate drainage flows during stable atmospheric conditions (experienced during day- or nighttime). A dividing streamline height is also used during stable atmospheric conditions when there is flow channeling and blocking from terrain features. Further adjustments to the wind field are described in Allwine and Bian (1995).</p> <p>TDM uses the output files from MET and TER and produces concentration and deposition fields on a user-specified receptor network for each time step of a simulation. The model computes source term characteristics, plume rise, contaminant transport, diffusion, puff depletion, radiological decay, and output parameters on the ground-level receptor grid. Detailed information is provided in Allwine and Bian (1995). All output fields are written to a binary file. These file are post-processed to generate graphical contour plots using ESRI's Map Objects software. The user can select any of the model's output products for display, look at results at specified output times, or animate the output display. All output products can be printed or transferred for display on other devices (including display using other GIS software products).</p>
5	Intended Application(s)	APGEMS is the primary atmospheric dispersion and dose assessment model for emergency planning, preparedness, and response applications at the U.S. Department of Energy Hanford Site. Versions of the model are used to address a wide range of applications, including emergency response, pesticide drift, and dust dispersion.
6	Strengths and Weaknesses	<p>Strengths:</p> <ul style="list-style-type: none"> • The model can be used for areas with uniform terrain or complex terrain. • APGEMS modular design allows its various components to be upgraded and

Table B.1 (cont.)

Id	Parameter	Description
		<p>replaced when appropriate.</p> <ul style="list-style-type: none"> • Developed specifically for the Hanford site. • Can use local real-time met data and can use data from any Hanford met data. Uses the met data in the format automatically provided by the met stations. • The model accounts for flow channeling, blocking by major terrain features, and drainage flows. • The model is simple to use with speedy performance. • Can be run in three different modes: Simple, Detailed, and Exercise. • Somewhat overcomes the limitation of using empirical diffusion coefficients based on relatively flat terrain, by adding a component of variance to the horizontal and vertical diffusion coefficients that represents enhanced diffusion caused by vertical wind shears. <p>Weaknesses:</p> <ul style="list-style-type: none"> • Not well-suited for near-field application (<100 m). • Developed for radiological releases.
7	Model Inputs	<ul style="list-style-type: none"> • Date and Release Location • Release Duration • Source Term: there are pre-populated sources, but all are radiological • Release scenario: user can choose pre-populated scenario or create one
8	Model Outputs	<p>APGEMS generates screen, hardcopy, and Internet-shareable output products. These products include plots of cumulative exposure, time-averaged concentration, and total effective dose equivalent (i.e., radiological dose). Model graphics and animations are designed to efficiently convey information to hazard analysts and decision-makers. The interface with the Internet allows information to be rapidly shared with emergency response personnel within an emergency operations center and at other control centers. It also calculates deposition fields.</p> <p>APGEMS develops maps with contour lines and tables showing exposures. If the simulation were run using the “First Responder Model,” “Cumulative Exposure” and “Time Averaged Concentration” are the only available output products. For releases involving radiological source terms, “Total Effective Dose Equivalent” and “Maximum Organ Dose” are also available choices. If the model were run in the Exercise Data Generation mode, additional instrument output products would also be available.</p>
9	Model Validation	Not to today’s standards.
10	Runtime Characteristics	Relatively fast
11	Computer Platform	Windows
12	Reference Document(s)	<p>PNNL. 2002. <i>User’s Guide for the Air Pollutant Graphical Environmental Modeling System (APGEMS)</i>. PNNL-14043, Pacific Northwest National Laboratory, Richland, WA.</p> <p>PNL. 1995. <i>PGEMS 2.0 – An Atmospheric Dispersion Model for Routine Air Quality Assessments and Emergency Response Applications</i>. PNL-12088, Pacific Northwest Laboratory, Richland, WA.</p>

Table B.2. American Industrial Hygiene Association Turbulent Eddy Diffusion Model Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	American Industrial Hygiene Association (AIHA) Turbulent Eddy Diffusion (AIHA-Eddy) model. The AIHA-Eddy model diffuses material at a constant rate from a point source based on a user-specified “turbulent diffusion coefficient.” The diffusion coefficient is assumed to be constant over space and space. The AIHA-Eddy model does not account for effects of plume rise, downwash/building wake, or terrain on pollutant concentrations downwind from a source. The AIHA-Eddy model provides estimates of air concentration as a function of time immediately downwind of a point source.
2	Model Developer	American Industrial Hygiene Association (AIHA)
3	Availability	The AIHA-Eddy model is freely available from their website: https://www.aiha.org/get-involved/VolunteerGroups/Documents/IHMOD_Korean-AIHA-MathModel209.xls
4	Model Description	The AIHA-Eddy model operates as a macro from within Microsoft Excel; there are four versions of the model that can be used to estimate concentrations: instantaneous (pulse) or continuous releases, with or without plume transport. The AIHA-Eddy model diffuses material at a constant rate from a point source based on a user-specified “turbulent diffusion coefficient.” The release can be instantaneous (pulse) or continuous, and the resulting plume can be transported downwind from the source. The diffusion coefficient is assumed to be constant over space and time. Conceptually, the AIHA-Eddy is similar to a molecular diffusion model, except the eddy diffusion rate is orders of magnitude larger than the molecular diffusion rate. The resulting concentration fields from the AIHA-Eddy model are symmetrical in shape. The AIHA-Eddy models do not account for effects of plume rise, downwash/building wake, or terrain on pollutant concentrations downwind from a source.
5	Intended Application(s)	The AIHA TED model is used to estimate concentrations as a function of time from an instantaneous or continuous point source. The model requires the user to specify an “eddy diffusivity coefficient,” which is assumed to be constant over space and time. Therefore, the AIHA TED model should only be used if the eddy diffusivity coefficient is well known and at transport distances very near the source (5-10 m).
6	Strengths and Weaknesses	Strengths: <ul style="list-style-type: none"> • The model is conceptually simple, quick, and easy to use. • The model and can be used to estimate concentration near (i.e., within meters) an instantaneous or continuous source. Weaknesses: <ul style="list-style-type: none"> • The user must specify an eddy diffusivity coefficient (m^2/min) that is representative of the thermal/mechanical turbulence in the atmosphere. • The AIHA (2009) provides estimates of eddy diffusivity coefficients for <i>indoor</i> applications that range from 0.1 to 10 m^2/min; however, it is not clear how these values translate to outdoor atmospheric diffusion. The AIHA (2009) further notes that there can be large uncertainty in assigning an eddy diffusivity coefficient.

Table B.2 (cont.)

Id	Parameter	Description
		<ul style="list-style-type: none"> • The eddy diffusivity coefficient is assumed to be constant in space in time, whereas atmospheric diffusion generally is not. For example, Gaussian plumes specify horizontal and vertical diffusion coefficients that are functionally different in space or time. Therefore, the model should only be used for outdoor atmospheric releases if the eddy diffusivity coefficient is well known and at transport distances very near the source. • The eddy diffusivity model does not account for plume reflection from the ground or the boundary layer. • The model does not account for the effects of plume rise, downwash/building wake, or terrain on pollutant concentrations downwind from a source.
7	Model Inputs	Source: point: total mass (instantaneous release) or emission rate (continuous release). Receptor Types: a single, discrete distance from the source. Meteorology: a wind speed and an eddy diffusion coefficient.
8	Model Outputs	Concentration as a function of time at a user-specified distance from the source.
9	Model Validation	The model (2009) is a simple diffusion model used to estimate concentrations near a point source. The model description (2009) discusses the use of this model for <i>indoor</i> dispersion, but does not explicitly discuss applications for outdoor dispersion. The AIHA (2009) writeup references several papers that have used the turbulent eddy diffusion model for indoor dispersion applications.
		The AIHA (2009) provides estimates of eddy diffusivity coefficients for <i>indoor</i> applications that range from 0.1 to 10 m ² /min; however, it is not clear how these values translate to outdoor atmospheric diffusion. The AIHA (2009) further notes that there can be large uncertainty in assigning an eddy diffusivity coefficient.
10	Runtime Characteristics	Less than a second.
11	Computer Platform	Windows Excel
12	Reference Document(s)	AIHA. 2009. <i>Mathematical Models for Estimating Occupational Exposure to Chemicals</i> , 2nd Edition, C Keil, editor.

Table B.3. CALPUFF Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>CALPUFF (Exponent Engineering and Scientific Consulting)</p> <p>CALPUFF is an integrated Lagrangian puff modeling system used to simulate atmospheric pollution dispersion. CALPUFF has been adopted by the U.S. Environmental Protection Agency (EPA) in its Guideline on Air Quality Models as the preferred model for assessing long range transport of pollutants and their impacts on Federal Class I areas and on a case-by-case basis for certain near-field applications involving complex meteorological conditions.</p>
2	Model Developer	<p>Sigma Research Corporation (SRC). Development was funded by the California Air Resources Board in the 1980s. Lead developer: Joseph Scire.</p>
3	Availability	<p>CALPUFF (and other associated models and code) are provided by Exponent, Inc. with a no-cost, limited-use license subject to some restrictions.</p>
4	Model Description	<p>The CALPUFF Modeling System includes three main components: CALMET, CALPUFF, and CALPOST. In the simplest terms, CALMET is a meteorological model that develops hourly wind and temperature fields on a three-dimensional gridded modeling domain. CALPUFF is a transport and dispersion model that advects “puffs” of material emitted from modeled sources, simulating dispersion and transformation processes along the way. In doing so, it typically uses the fields generated by CALMET, or as an option, it may use simpler non-gridded meteorological data much like existing plume models. The primary output files from CALPUFF contain either hourly concentrations or hourly deposition fluxes evaluated at selected receptor locations. CALPOST is used to process these files, producing tabulations that summarize the results of the simulation. Most applications of the system are built around these three components. To enhance their functionality, a PC-based GUI is provided for each major component. The GUIs can be used to prepare the control file that configures a run, execute the corresponding component model, and conduct file management functions. The GUIs also contain an extensive help system that makes much of the technical information contained in this manual available to the user online. The modeling system may also be setup and run without the aid of the GUIs. The control file for each component is simply a text file that is readily edited, and it contains extensive information about model options, default values, and units for each variable.</p> <p>CALPUFF is a multi-layer, multi-species, non-steady-state puff dispersion model that can simulate the effects of time- and space-varying meteorological conditions on pollutant transport, transformation, and removal. CALPUFF can use the three-dimensional meteorological fields developed by the CALMET meteorological model or single-station winds data. However, single-station winds should be used with caution because they do not allow CALPUFF to take advantage of its capabilities to treat spatially variable meteorological fields. CALMET includes a diagnostic wind field generator, and overland and overwater boundary layer modules. CALMET has the ability to combine the wind fields generated by the CSUMM prognostic wind field model or the MM5/MM4 model with observational data through an objective analysis procedure. CALPUFF contains algorithms for near-source effects such as building downwash, transitional plume rise, partial plume penetration, and subgrid scale terrain interactions, as well as longer range effects such as pollutant removal (wet scavenging and dry deposition), chemical transformation, vertical wind shear, overwater transport, and coastal interaction effects. It can accommodate arbitrarily varying point source and gridded area source emissions. Most of the algorithms contain options to treat the physical processes at different levels of detail depending on the model application.</p>

Table B.3 (cont.)

Id	Parameter	Description
		<p>Some of the specific features of CALPUFF include the following.</p> <p>Various Source Types:</p> <ul style="list-style-type: none"> • Point sources (constant or variable emissions) • Line sources (constant or variable emissions) • Volume sources (constant or variable emissions) • Area sources (constant or variable emissions) <p>Non-steady-state Emissions and Meteorological Conditions:</p> <ul style="list-style-type: none"> • Gridded 3D fields of meteorological variables (winds, temperature) • Spatially-variable fields of mixing height, friction velocity, convective velocity scale, Monin-Obukhov length, precipitation rate • Vertically and horizontally varying turbulence and dispersion rates • Time-dependent source and emissions data <p>Efficient Sampling Functions:</p> <ul style="list-style-type: none"> • Integrated puff formulation • Elongated puff (slug) formulation <p>Dispersion Coefficient (σ_y, σ_z) Options:</p> <ul style="list-style-type: none"> • Direct measurements of σ_v and σ_w • Estimated values of σ_v and σ_w based on similarity theory • Pasquill-Gifford (PG) dispersion coefficients (rural areas) • McElroy-Pooler (MP) dispersion coefficients (urban areas) • CTDM dispersion coefficients (neutral/stable) <p>Vertical Wind Shear:</p> <ul style="list-style-type: none"> • Puff splitting • Differential advection and dispersion <p>Plume Rise:</p> <ul style="list-style-type: none"> • Partial penetration • Buoyant and momentum rise • Stack tip effects • Vertical wind shear • Building downwash effects <p>Building Downwash:</p> <ul style="list-style-type: none"> • Huber-Snyder method • Schulman-Scire method
5	Intended Application(s)	<p>CALPUFF was originally designed for modeling long-range transport of pollutants in California. It can provide time averaged information from 1 hour to 1 year.</p> <p>CALPUFF includes modules for complex terrain effects, overwater transport, coastal interaction effects, building downwash, wet and dry removal, and simple chemical transformation. It is intended to operate over domains tens of meters to hundreds of kilometers in size.</p>

Table B.3 (cont.)

Id	Parameter	Description
6	Strengths and Weaknesses	<p>Strengths: CALPUFF is a thoroughly tested model, and uses state-of-the science boundary layer theory to estimate air concentrations downwind of a source. Ability to model in a forecast mode could also be useful.</p> <p>Weaknesses: CALPUFF is not intended to model short time intervals over small spatial scales. Modeling within a tank farm for acute exposures is not an ideal application for this model.</p>
7	Model Inputs	<p>Source:</p> <ul style="list-style-type: none"> • Point: emission rate, gas exit temperature, inside stack diameter, gas exit velocity, gas exit flow rate • Area: emission rate, length, width, orientation angle from true north, initial vertical dimension • Volume: emission rate, length of side, initial lateral dimension, initial vertical dimension • Line: emission rate, length, width, initial vertical dimension <p>Receptor Types: discrete, Cartesian, and/or polar</p> <p>Meteorology Required:</p> <ul style="list-style-type: none"> • Can run on single point data • Can integrate multiple input sources • Can use predicted wind field data to operate in a forecast mode • Can use upper air data or interpret from surface measurements
8	Model Outputs	Tabular outputs of hourly averages or other user-defined averaging periods for the defined receptors.
9	Model Validation	<p>Official model validation was not done as part of the development. However, in the 20+ years since its release, many peer-reviewed journal articles have been published documenting the accuracy of both CALPUFF and CALMET.</p> <p><i>One example:</i> Chang et al. 2010. Evaluations of CALPUFF, HPAC, and VLSTRACK with Two Mesoscale Field Datasets. <i>Journal of Applied Meteorology</i>, 42, 453–466 http://journals.ametsoc.org/doi/abs/10.1175/1520-0450%282003%29042%3C0453:EOHAV%3E2.0.CO;2</p>
10	Runtime Characteristics	Varies depending on the number of sources, receptors, species, and length of run, but generally a few minutes.
11	Computer Platform	Windows 7. All will run in XP. GUIs are 16-bit and will not run on 64-bit machines (Windows 7). Some GUIs may require an XP emulator. With minor adjustments can be run on Unix and Linux
12	Reference Document(s)	Scire et al. 2000. <i>A User's Guide for the CALPUFF Dispersion Model (Version 5)</i> . http://www.src.com/calpuff/download/CALPUFF_UsersGuide.pdf .

Table B.4. SCIPUFF Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>SCIPUFF (Second-Order Closure Integrated Puff) Model</p> <p>SCIPUFF is a Lagrangian puff dispersion model that uses a collection of Gaussian puffs to represent an arbitrary, three-dimensional, time-dependent concentration field. The turbulent diffusion parameterization is based on modern turbulence closure theory, specifically the second-order closure model of Donaldson (1973) and Lewellen (1977), which provides a direct relationship between the predicted dispersion rates and the measurable turbulent velocity statistics of the wind field. In addition to the average concentration value, the closure model also provides a prediction of the statistical variance in the concentration field resulting from the random fluctuations in the wind field. The closure approach also provides a direct representation for the effect of averaging time (Sykes and Gabruk 1997).</p>
2	Model Developer	<p>Originally developed by Dr. R. Ian Sykes, Titan Research & Technology, ARAP Group (Titan seems to now be defunct.)</p> <p>As a courtesy, Sage Management makes available for download this public domain version of SCIPUFF, known as PC-SCIPUFF Model (Version 1.2PD31.5) 7/18/2000.</p>
3	Availability	<p>PC-SCIPUFF (Version 1.2PD31.5) 7/18/2000, the public domain version, is freely available at http://www.sage-mgt.net/services-and-solutions/modeling-and-simulation/pc-scipuff-download</p>
4	Model Description	<p>SCIPUFF is a Lagrangian puff dispersion model that uses a collection of Gaussian puffs to represent an arbitrary, three-dimensional, time-dependent concentration field. The turbulent diffusion parameterization is based on modern turbulence closure theory, specifically the second-order closure model of Donaldson (1973) and Lewellen (1977), which provides a direct relationship between the predicted dispersion rates and the measurable turbulent velocity statistics of the wind field. In addition to the average concentration value, the closure model also provides a prediction of the statistical variance in the concentration field resulting from the random fluctuations in the wind field. The closure approach also provides a direct representation for the effect of averaging time (Sykes and Gabruk 1997).</p> <p>Shear distortion is accurately represented using the full Gaussian spatial moment tensor, rather than simply the diagonal moments, and an efficient puff splitting/merging algorithm minimizes the number of puffs required for a calculation. In order to increase calculation efficiency, SCIPUFF uses a multi-level time stepping scheme with an appropriately sized time-step for each puff. An adaptive multi-grid is used to identify neighboring puffs in the spatial domain, which greatly reduces the search time for overlapping puffs in the interaction calculation and puff-merging algorithm. Static puffs are used to represent the steady-state phase of the plume near the source and are updated only with the meteorology, also decreasing the number of puffs needed for the calculation.</p> <p>SCIPUFF can model many types of source geometries and material properties. It can use several types of meteorological input, including surface and upper-air observations or three-dimensional gridded data. Planetary boundary layer turbulence is represented explicitly in terms of surface heat flux and shear stress using parameterized profile shapes. A graphical user interface (GUI) that runs on a PC is used to define the problem scenario, run the dispersion calculation and produce color contour plots of resulting concentrations. The GUI also includes online help.</p>

Table B.4 (cont.)

Id	Parameter	Description
		<p>Features:</p> <ul style="list-style-type: none"> • Continuous, instantaneous, moving, and stack sources • Gaseous and particulate materials • Buoyant and non-buoyant releases • Complex terrain effects and mass-consistent wind-field adjustment • Dry deposition • Wet deposition and gravitational settling of particles • Linear decay of released materials • Short and long range transport • Fixed winds, surface or profile observations or gridded meteorological input accepted • Time-history concentration sampling capability (i.e., receptors) <p>Enhanced Features:</p> <ul style="list-style-type: none"> • Estimates the uncertainty in the concentration field. • Performs accurate treatment of wind shear. • Merges puffs in addition to splitting them using an efficient adaptive multi-grid scheme. • Uses an efficient adaptive time-stepping scheme. • Utilizes static puffs near the source to reduce computation time. • Flexible output displays color contour plots of concentration and probabilities of exceeding user-specified concentrations. <p>Source-Receptor Relationships: The time-dependent concentrations are calculated as the sum of the contribution from all puffs. The maximum number of continuous sources is 400. The maximum number of instantaneous sources is limited by the maximum number of puffs, which is 20,000. The maximum number of discrete receptors is 200. SCIPUFF uses an adaptive grid to compute concentrations on a plane and produces color contour plots upon the completion of a run. If desired, discrete receptors or grid receptor concentration values may be exported from the contour plot to an ASCII file. To obtain the individual contribution from each source, no additional runs are necessary; however, an extra pollutant needs to be released from each source that has the same properties as the pollutant of interest but a unique name.</p> <p>Plume Behavior: Plume rise is treated through the conservation of buoyancy and momentum. A turbulent entrainment model based on earlier work on power plant plume rise (Sykes et al. 1988) relates the turbulent velocity to the vertical rise rate. Complex terrain is treated through the reflection in the local surface tangent plane. Fumigation is treated explicitly according to the modeled boundary layer behavior. Aerodynamic downwash is not treated.</p> <p>Horizontal Winds: Horizontal winds may be specified by the user as constant, provided in a time-dependent, three-dimensional gridded meteorological file, or in multiple surface observations and/or upper-air profiles. Surface data and vertical profiles from multiple stations are interpolated in space and time. The arbitrary spatial locations at each observation time are interpolated onto a grid using a simple inverse square weighting. Velocity (and temperature) fields are then interpolated between the grid times to provide smoothly varying meteorology for the dispersion calculation. In the surface layer, a similarity profile that accounts for surface roughness and stability is used. A three-dimensional mass-consistent wind field may be generated optionally.</p>

Table B.4 (cont.)

Id	Parameter	Description
		<p>Vertical Wind Speed: Unless provided in a time-dependent, three-dimensional gridded meteorological file, vertical wind speed is assumed zero. A three-dimensional mass-consistent wind field may be generated optionally.</p> <p>Horizontal Dispersion: Puff growth is based on second-order closure turbulence modeling involving the horizontal turbulent velocity fluctuations and length scales that are either provided as input or modeled. Wind shear effects are also treated. The effect of averaging time is explicitly represented by selectively filtering the assumed turbulence spectrum.</p> <p>Vertical Dispersion: Puff growth is based on second-order closure turbulence modeling involving the vertical turbulent velocity fluctuations and length scales that are either provided as input or modeled. Turbulent vertical drift, buoyancy-forces and wind shear effects are also treated. Perfect reflection is assumed at the ground surface and, for a convective boundary layer, at the mixing height. The effect of averaging time is explicitly represented by selectively filtering the assumed turbulence spectrum.</p> <p>Chemical Transformation: Linear chemical transformations are treated using exponential decay (decay rate is provided by the user).</p> <p>Physical Removal: Deposition of gases and particles, and precipitation washout and gravitational settling of particles are treated. Gaseous dry deposition effects are based on a fixed deposition velocity provided by the user. Dry deposition of particles to vegetative canopies is based on the approach of Slinn (1982), which includes determining a particle deposition efficiency. Dry deposition of particles to non-vegetative rough surfaces and water is treated according to Lewellen and Sheng (1980). Gravitational settling effects are determined by the particle fall velocity, which is obtained from the balance between gravitational acceleration and the aerodynamic drag force. Precipitation washout of particles is treated using a scavenging coefficient that is a function of precipitation rate and particle size following the approach of Seinfeld (1986). Precipitation washout of gases is not treated.</p>
5	Intended Application(s)	<p>SCIPUFF is appropriate for modeling both short and long range (greater than 50 km) transport, steady or non-steady state emissions of primary pollutants (gases or particles), buoyant or neutral sources using time-dependent meteorological data (surface, profile, or gridded). Shear distortion, complex terrain, linear chemical transformations, gravitational settling, and deposition are treated. In addition to the mean concentration, dose, and deposition, SCIPUFF provides an estimate of the probability levels of the predicted values. The model may be used on a case-by-case basis.</p>
6	Strengths and Weaknesses	<p>SCIPUFF may be used to model the dispersion of primary pollutants (gases or particles) which are inert or undergo linear chemical reactions, e.g., CO, NO, SO, PM-10, PM-2.5.</p> <p>Strengths: uses advanced turbulence schemes to model puff growth, includes 3D meteorological processor.</p> <p>Weaknesses: Not ideal for a small spatial scale (e.g., tank farm). Performed poorly in a field tracer test at distances less than 100 m and light wind speeds (see validation).</p>
7	Model Inputs	<p>Source Data:</p> <ul style="list-style-type: none"> • Pollutant physical and chemical properties are input by the user, including the chemical decay rates and deposition velocities. Multiple pollutants may be defined

Table B.4 (cont.)

Id	Parameter	Description
		<p>for a single release and size distributions may be defined for particles.</p> <ul style="list-style-type: none"> • Release types are specified, e.g., continuous (arbitrary duration), instantaneous, mobile, and stack sources. Input requirements for each source depend on the release type and include emission rate and duration for each material type and size group as well as source coordinates, elevation and size. <p>Meteorological Data (different forms of meteorological input can be used by SCIPUFF):</p> <ul style="list-style-type: none"> • Fixed winds: Wind speed and direction is assumed constant. • Observational input: Time-dependent observations are combined from multiple surface stations and/or upper-air profiles. A pre-processor is available that can be used to convert input to the Industrial Source Complex Short Term (ISCST) model to SCIPUFF's input format for surface data. • Time-dependent, three-dimensional gridded input. <p>Terrain data can be included with the gridded meteorological input files or provided as a separate file for other input types.</p> <p>Turbulence Data (two types of turbulence input may be specified optionally):</p> <ul style="list-style-type: none"> • Planetary boundary layer: Vertical profiles of the boundary layer scale turbulent velocity fluctuations, heat flux, and turbulence length scales can be provided as input by the user or modeled based on boundary layer characteristics. Options for treatment of the boundary layer include "calculated," "observed," or "simple diurnal." Input requirements depend on boundary layer treatment type. • Large scale variability: For long-range transport, the mesoscale horizontal velocity. • Fluctuations and turbulence length scale may be specified by the user, computed from a theoretical model or read from a meteorological observation file. <p>Other Input:</p> <p>Receptor locations are provided by the user in a "sampler" file that includes the receptor locations and heights and the name of the material to be sampled. Other data requirements include the coordinates of the domain, duration of the calculation, averaging time and user-specified model options.</p>
8	Model Outputs	<p>Color contour plots can be viewed upon completion of a run at user-specified times. Available plots include horizontal instantaneous slice, vertical instantaneous slice, vertically integrated slice, integrated surface dose, and integrated surface deposition for either the mean concentration or probability levels. The user can input the desired location of the slices and view these locations one at a time after completion of the run. Plots can be animated over the simulation time based on user-specified time intervals.</p> <p>Tables of data (in ASCII-format) can be exported from the plots by clicking on desired locations with the mouse or a grid may be specified.</p> <p>If a sampler (i.e., receptor) file was specified on input, an ASCII file of time-dependent concentrations at each sampler location is produced as output. Surface integrals of dose and deposition are stored as adaptive grid files with multiple time breaks in direct access binary format. The puff file is a binary file that contains the complete puff data at a number of time breaks.</p>

Table B.4 (cont.)

Id	Parameter	Description
9	Model Validation	<p>http://journals.ametsoc.org/doi/full/10.1175/1520-0450%281997%29036%3C1038%3AASOCMF%3E2.0.CO%3B2</p> <p>SCIPUFF has been validated against a number of classical laboratory and field experiments, demonstrating its usefulness for general atmospheric dispersion applications. It has been recommended as an alternative model by the EPA, which can be used on a case-by-case basis for regulatory applications. In 2000, a public domain version of SCIPUFF was submitted to the EPA by Titan Corporation as an EPA Alternative Model.</p> <p>An inter-comparison of SCIPUFF, ALOHA, and EPIcode with tracer data is also shown here: http://www.osti.gov/scitech/servlets/purl/934686.</p>
10	Runtime Characteristics	Typically a few minutes.
11	Computer Platform	SCIPUFF is a Windows-based product and is known to run on 32-bit Windows NT, 2000, XP, and Vista. It has also been run on 64-bit Windows 7 Home Premium.
12	Reference Document(s)	Sykes RI, SF Parker, DS Henn, CP Cerasoli, and LP Santos. 1998. <i>PC-SCIPUFF Version 1.2PD Technical Documentation</i> . ARAP Report No. 718. Titan Corporation, Titan Research & Technology Division, ARAP Group, P.O. Box 2229, Princeton, NJ, 08543-2229.

Appendix C

Particle Model Detailed Summary Tables

Appendix C - Particle Model Detailed Summary Tables

Table C.1. ADAPT/LODI Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>NARAC (National Atmospheric Release Advisory Center)</p> <p>NARAC is a national support and resource center for emergency planning, real-time assessment, emergency response, and detailed studies of atmospheric releases of nuclear, radiological, chemical, biological, and hazardous natural materials. It is located at the Department of Energy/National Nuclear Security Administration's (DOE/NNSA) Lawrence Livermore National Laboratory (LLNL).</p>
2	Model Developer	NARAC, which is located at the DOE/NNSA LLNL.
3	Availability	<p>Web-based software provided to authorized users here: https://naracweb.llnl.gov/web/support/requestAccount.html;jsessionid=D6FD4A3AB6E8187AD67BCAD3B82139D8.</p>
4	Model Description	<p>NARAC is more than just a “model.” It consists of a suite of web-based software tools and components that provides a rapid and user-friendly access to NARAC predictions via the Internet. A customized Web entry point, CMweb, serves as the unified DOE/NNSA Consequence Management Web site for the distribution of Federal Radiological Monitoring Assessment Center (FRMAC) consequence management data and data products, as well as NARAC model predictions. A separate international eXchange Program (IXP) site supports the International Atomic Energy Agency (IAEA) and member states under DOE/NNSA auspices. The NARAC Web services other users of the center. All three websites are protected using user logins and passwords, encrypted (https) communications, and restricted sharing of information to specific users or groups of users.</p> <p>The NARAC, CM, and IXP websites allow authorized users to:</p> <ul style="list-style-type: none"> • Access 3D plume model results provided by NARAC expert analysts • Share NARAC model results, data and other event information with other users or groups of users • Generate their own plume model simulations using real-time weather data, numerical weather prediction model output, or their own user-input weather information <p>NARAC software automates the process of extracting the relevant data for the period and location of interest, handles model execution, and generates the final model products. The schematic flow chart below illustrates some of the primary pathways through the system and shows the coupling of the Atmospheric Data Assimilation and Parameterization Techniques (ADAPT) model and the Lagrangian Operational Dispersion Integrator (LODI) model. ADAPT and LODI run on variable resolution meteorological and concentration grids that are generated by the Grid Generator (GridGen) utility. In addition, NARAC’s modeling system includes source term and other specialized models, for calculating the impacts of specific types of releases.</p> <p>Atmospheric Data Assimilation and Parameterization Techniques (ADAPT): The ADAPT model constructs 3D fields of key variables such as the mean winds, pressure, precipitation, temperature, and turbulence, from meteorological observations or numerical weather prediction output, including NARAC’s in-house version of Weather Research and Forecasting (WRF) model.</p>

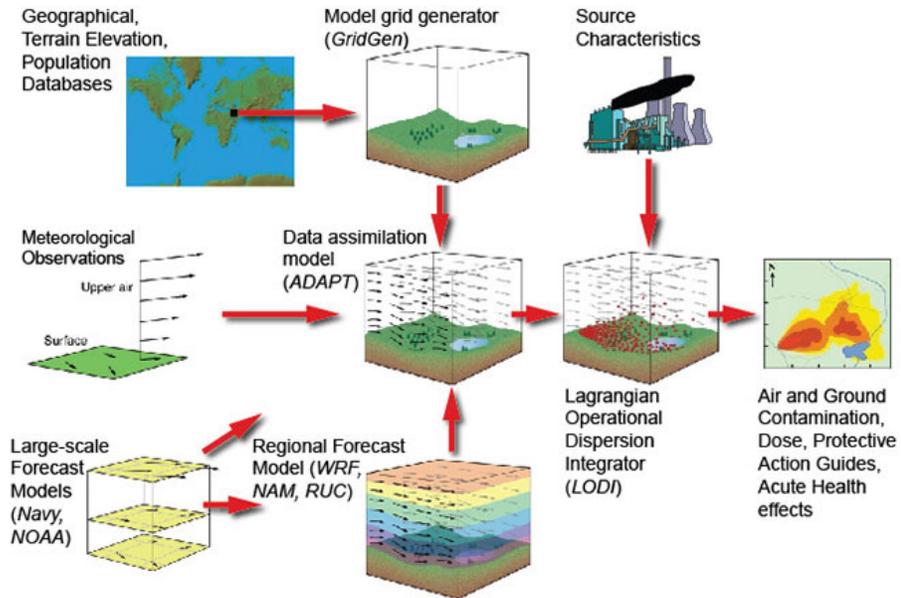
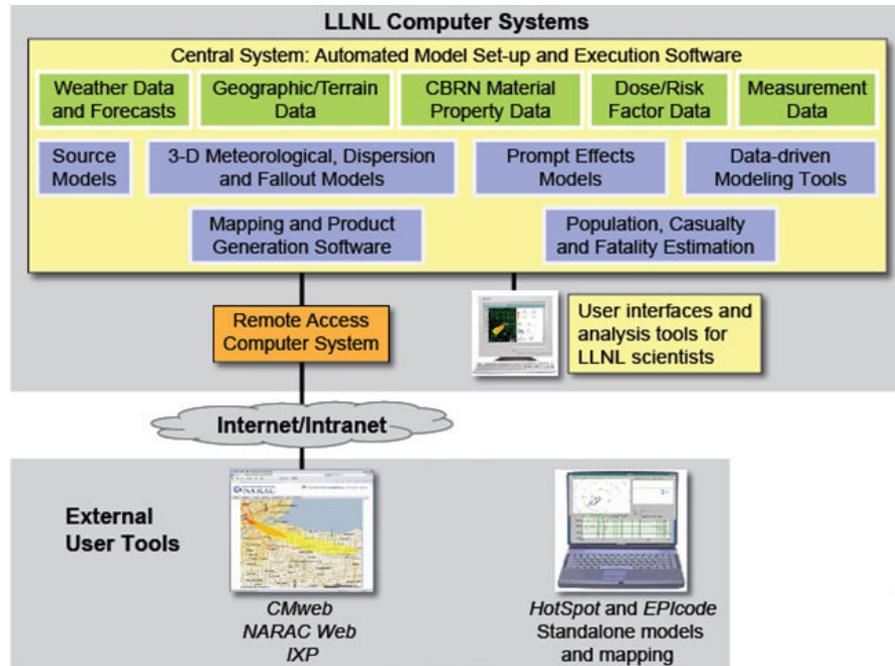
Table C.1 (cont.)

Id	Parameter	Description
		<p>Lagrangian Operational Dispersion Integrator (LODI) model: The LODI particle dispersion model solves the 3D advection-diffusion equation using a Lagrangian stochastic, Monte Carlo method, and the meteorological fields produced by the ADAPT model. LODI simulates the processes of mean wind advection and turbulent diffusion, along with radioactive decay and production, biological-agent degradation, first-order chemical reactions, gravitational settling, dry deposition, and wet deposition from precipitation effects. LODI also incorporates modules for specialized applications such as buoyant and momentum plume rise. Other key LODI features include treatment of:</p> <ul style="list-style-type: none"> • Aerosol mass-size distributions, specified either as a log-normal distribution or as a table of distinct mass fractions and size ranges • First-order decay of biological and chemical material • Decay and production of mixtures of radioisotopes during atmospheric transport • Dry deposition based on gravitational settling velocity and deposition resistance • Precipitation scavenging based on aerosol size and spatially and temporally varying precipitation rates • Weathering and resuspension <p>Some release scenarios require detailed modeling of complex source geometries or the early time-evolution of the hazardous plume. These scenarios are modeled either by incorporating software directly into LODI or by running separate term models that calculate the initial source characteristics. Examples include:</p> <ul style="list-style-type: none"> • Thermal buoyancy-driven or momentum-driven plume rise from a stack or vent that causes the material to rise above the opening from which the material is emitted • Thermal buoyancy-driven plume rise caused by a fire • Thermal buoyancy-driven cloud rise from a high-explosive detonation, such as a radiological dispersal device or “dirty bomb” • Buoyancy-driven cloud rise from a nuclear detonation • Release and subsequent evaporation rates from liquid chemical spills or sprayers <p>LODI includes algorithms to model emissions involving stack releases or fires. These plume rise algorithms simulate the initial vertical rise and spread of the plume until the time it becomes neutrally buoyant. The methods are based on an integral model and solve equations for the total fluxes of mass, momentum and thermodynamic energy through a plume cross-section taking into account the ambient turbulence, thermal stratification, and temperature inversions that can limit the height of the plume rise.</p>

Table C.1 (cont.)

Id	Parameter	Description
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NARAC Modeling Suite Architecture Figures



5 Intended Application(s)

The NARAC modeling system provides 3D worldwide plume model predictions. Automated software is used to generate standard products in 5 to 10 minutes. NARAC analysts use advanced capabilities of the system to develop refined products based on field data and provide customized quality-assured products on request.

Table C.1 (cont.)

Id	Parameter	Description
6	Strengths and Weaknesses	<p>Strengths: Powerful modeling suite, with integrated databases</p> <p>Weaknesses: Not run locally (run on LLNL computer system, accessed through internet). Not ideal for small spatial scales (e.g., tank farm).</p>
7	Model Inputs	<p>Data feeding into the model grid generator (GridGen) component:</p> <ul style="list-style-type: none"> • Geographical, terrain elevation, and population databases <p>Data feeding into the ADAPT component:</p> <ul style="list-style-type: none"> • Surface and upper air meteorological observations <ul style="list-style-type: none"> ○ Weather observations are collected in real-time to provide input to ADAPT. These observations are acquired from world-wide surface, tower, balloon sounding, and profiler measurement stations provided by NOAA, the DOD, Kennedy Space Center, WeatherBug, and “mesonets.” • Large and regional-scale forecast models <ul style="list-style-type: none"> ○ Gridded forecast and analysis field made available by the NOAA, the Air Force Weather Agency, and the Fleet Numerical Meteorology and Oceanography Center (FNMOC), or produced using NARAC’s in-house NWP model WRF. • Grid output from the GridGen component. <p>Data feeding into the LODI component:</p> <ul style="list-style-type: none"> • Source Characteristics <ul style="list-style-type: none"> ○ Radiological, chemical, or biological materials in gaseous, liquid, or solid form. Multiple hazardous material sources can be modeled in a single LODI run using point, line, area, sphere, or Gaussian-shaped source geometries, moving as well as static sources, and time-varying emission rates. Additional specialized source term algorithms describe the detailed time evolution of the source geometry when these cannot be adequately represented by basic geometric shapes, including: <ul style="list-style-type: none"> ▪ Thermal and/or momentum driven plume rise from a stack, vent, or fire ▪ Detonation of chemical high explosives ▪ Nuclear detonations resulting in distinct base surge, stem, and cap clouds • Output from the ADAPT component
8	Model Outputs	<p>Model grid generator (GridGen):</p> <ul style="list-style-type: none"> • Variable resolution continuous-terrain grids used for the ADAPT and LODI simulations. <p>ADAPT:</p> <ul style="list-style-type: none"> • 3D meteorological fields used in the LODI dispersion calculations (e.g., winds, temperature, pressure, humidity, precipitation). • Turbulence variables are determined from meteorological and land-surface data using similarity-theory turbulence scaling relationships and surface energy budget methods. • Produces non-divergent wind fields using an adjustment procedure based on the variational principle and a finite-element discretization. The finite element method is effective for treating complex terrain and dealing with variable resolution grids. The solution is obtained via a choice of conjugate gradient solvers and use of a stabilization matrix to improve computational efficiency.

Table C.1 (cont.)

Id	Parameter	Description
LODI:		<ul style="list-style-type: none"> • Predicted 2D and 3D gridded concentrations of hazardous material released into the atmosphere. • Time series of instantaneous and time-integrated air concentrations and ground deposition. • Air or ground contamination, dose, and health effects resulting from the hazardous material release. • Model results can also be converted to specific levels of concern, such as EPA/DHS protective action guide levels for radiological releases, EPA/AIHA/DOE chemical exposure guideline levels for chemical releases, or biological agent lethal dose probabilities. • View plume model predictions at different resolutions superimposed on maps showing highways, local streets, political boundaries, water features, major landmarks or aerial/satellite imagery. • Save NARAC modeling results as one-page technical plots, multi-page comprehensive Consequence Reports, or Briefing Products in a variety of formats (HTML, PowerPoint, PDF). • Output NARAC plume modeling results in Google Earth .kmz or GIS Shape formats for use in other Geographical Information Systems. • Probe points on a map to determine predicted contamination and dose values at multiple points.
9	Model Validation	<p>NARAC models are extensively tested and evaluated against exact mathematical solutions to the model equations, controlled laboratory and field experiments, and real-world releases. These tests ensure that NARAC models meet the following criteria:</p> <ul style="list-style-type: none"> • Physically realistic equations and parameterizations are used in the models. • Model equations are solved correctly and numerical methods are sufficiently accurate. • Necessary input data are available to drive the models, including meteorological, geographical, and material/release properties. • Models are accurate enough to reproduce data from tracer experiments to real-world incidents. • Models are fast and robust enough to be used for emergency response applications. • Software meets DOE Software Quality Assurance standards. <p>NARAC uses experimental data from tracer gas and explosive dispersal releases to evaluate the accuracy of its models on local, regional, and continental scales. NARAC models have performed in the top tier of models in international model evaluation and inter-comparison studies such as post-accident modeling of the Chernobyl accident, and the European Tracer Experiment. Comparisons with data show that NARAC model predicted values are typically within a factor of 2 of measured values for simpler cases (relatively flat terrain and steady-state meteorological conditions) and within a factor of 5–10 of measured values for more complex conditions (e.g., heterogeneous terrain, time-varying meteorology, or complicated emissions). Factor of 2 agreement means that the ratio of observed to predict values are between 1/2 and 2. Even in complex conditions, predicted peak air and ground contamination values are typically within a factor of 2 of measured values for the same downwind distance, but not necessarily the same exact location.</p> <p>Real-world incidents provide opportunities to test models under complex conditions. NARAC has responded to numerous events since its creation in 1979. Examples</p>

Table C.1 (cont.)

Id	Parameter	Description
		include the Chernobyl nuclear power plant accident, industrial fires and accidents, the Algeciras Spain Cesium release, the Tokaimura Japan criticality accident, and the Fukushima Dai-Ichi Nuclear Power Plant accident.
		Official Evaluation Report using Copenhagen and OLAD data - https://narac.llnl.gov/content/mods/publications/op-model-description-evaluation/UCRL-AR-217329.pdf
10	Runtime Characteristics	Variable (like the others), but generally within a few minutes.
11	Computer Platform	Can only be run in client-server mode online.
12	Reference Document(s)	There are many publications and reference documents associated with the NARAC suite of tools, models, and components. They can be found here: https://narac.llnl.gov/about/publications .
		Notable user manual guides include:
		<i>NARAC Technical Plot Guide: A Guide to NARAC Predictions and Analyses -</i> https://narac.llnl.gov/content/mods/publications/user-guides-documentation/LLNL-PRES-636839.pdf .
		<i>Lagrangian Operational Dispersion Integrator (LODI) User's Guide Version 1.0 -</i> https://narac.llnl.gov/content/mods/publications/user-guides-documentation/UCRL-AM-212798.pdf .

Table C.2. HYSPLIT Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) (National Oceanic and Atmospheric Administration)</p> <p>The HYSPLIT model is a complete system for computing simple air parcel trajectories, as well as complex transport, dispersion, chemical transformation, and deposition simulations. The model calculation method is a hybrid between the Lagrangian approach (puff), and the Eulerian methodology, which uses a fixed three-dimensional grid to compute pollutant air concentrations (particle dispersion). The HYSPLIT model can be run interactively on the READY web site or installed on computer and run using a graphical user interface (GUI).</p>
2	Model Developer	National Oceanic and Atmospheric Administration and the Australian Bureau of Meteorology
3	Availability	Free download, or can be run directly from the web in a client-server mode.
4	Model Description	<p>The HYSPLIT model is a complete system for computing simple air parcel trajectories, as well as complex transport, dispersion, chemical transformation, and deposition simulations. A common application is a back trajectory analysis to determine the origin of air masses and establish source-receptor relationships. The model calculation method is a hybrid between the Lagrangian approach, using a moving frame of reference for the advection and diffusion calculations as the trajectories or air parcels move from their initial location, and the Eulerian methodology, which uses a fixed three-dimensional grid as a frame of reference to compute pollutant air concentrations.</p> <p>In the puff model, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into several new puffs, each with its share of the pollutant mass. In the particle model, a fixed number of particles are advected about the model domain by the mean wind field and spread by a turbulent component. Some of the important features are listed below.</p> <p>Trajectories:</p> <ul style="list-style-type: none"> • Single or multiple (space or time) simultaneous trajectories • Optional grid of initial starting locations • Computations forward or backward in time • Trajectory ensemble option using meteorological variations • Output of meteorological variables along a trajectory • Integrated trajectory clustering option <p>Air Concentrations:</p> <ul style="list-style-type: none"> • 3D particle dispersion or splitting puffs • Instantaneous or continuous emissions, point or area sources • Multiple resolution concentration output grids • Fixed concentration grid or dynamic sampling • Wet and dry deposition, radioactive decay, and resuspension • Emission of multiple simultaneous pollutant species • Integrated dust-storm emission algorithm • Mass can be transferred to a Eulerian module for global-scale simulations

Table C.2 (cont.)

Id	Parameter	Description
5	Intended Application(s)	<p>Meteorology:</p> <ul style="list-style-type: none"> • Model can run with multiple nested input data grids • Links to ARL and NWS meteorological data server • Access to forecasts and archives including NCAR/NCEP reanalysis • Additional software to convert other common data • Utility programs to display and manipulate meteorological data <p>Output Features:</p> <ul style="list-style-type: none"> • Model graphics displayed as Postscript files • Converters to many other formats: GIF, GrADS, ArcView, Vis5D <p>HYSPLIT is intended for longer range transport calculations. The minimum resolution is approximately 1 km. Validation cases use grid spacing of 9 and 300 km. The model is designed to support a wide range of simulations related to the atmospheric transport and dispersion of pollutants and hazardous materials, as well as the deposition of these materials to the Earth's surface. Some of the applications include tracking and forecasting the release of radioactive material, volcanic ash, wildfire smoke, and other pollutants on a regional scale.</p>
6	Strengths and Weaknesses	<p>Strengths: Ability to run online, ability to provide backward air parcel tracking, computational speed.</p> <p>Weaknesses: 1-km resolution (at best). Does not use surface wind data. Modeling within a tank farm is not an ideal application for this model.</p>
7	Model Inputs	<p>Source:</p> <ul style="list-style-type: none"> • Point: emission rate, gas exit temperature, inside stack diameter, gas exit velocity, gas exit flow rate • Area: emission rate, length, width, orientation angle from true north, initial vertical dimension <p>Meteorology Required:</p> <ul style="list-style-type: none"> • Uses existing meteorological databases • Requires data in ARL format • Needs upper air data- not surface data • Cannot use user supplied meteorological data
8	Model Outputs	<p>Primary output is a map-based output; concentration contours, deposition maps, trajectories. Gridded concentration and deposition files are available. An ASCII text file containing trajectory is available.</p>
9	Model Validation	<p>Since its release, many peer-reviewed journal articles have been published using HYSPLIT. Best example:</p> <p>Fong Ngan, Ariel Stein*, Roland Draxler, 2015: Inline Coupling of WRF-HYSPLIT: Model Development and Evaluation Using Tracer Experiments. <i>Journal of Applied Meteorology and Climatology</i>, 54, 1162-1176, doi: 10.1175/JAMC-D-14-0247.1.</p>
10	Runtime Characteristics	<p>Varies depending on the number of sources, receptors, species, and length of run, but generally a few minutes.</p>
11	Computer Platform	<p>PC, Mac, Linux. Can also be run in client-server mode online. The web version configuration has limitations to avoid computational saturation of the web server.</p>

Table C.2 (cont.)

Id	Parameter	Description
12	Reference Document(s)	<p>Stein AF, RR Draxler, GD Rolph, BJB Stunder, MD Cohen, and F Ngan. 2015. "NOAA's HYSPLIT atmospheric transport and dispersion modeling system." <i>Bull. Amer. Meteor. Soc.</i> 96:2059-2077, http://dx.doi.org/10.1175/BAMS-D-14-00110.1</p> <p>Draxler RR, 1999. <i>HYSPLIT4 user's guide</i>. NOAA Tech. Memo. ERL ARL-230, NOAA Air Resources Laboratory, Silver Spring, MD.</p> <p>Draxler RR and GD Hess. 1998. "An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition." <i>Aust. Meteor. Mag.</i>, 47:295-308.</p> <p>Draxler RR and GD Hess, 1997. <i>Description of the HYSPLIT_4 modeling system</i>. NOAA Tech. Memo. ERL ARL-224, NOAA Air Resources Laboratory, Silver Spring, MD, 24 pp.</p>

Table C.3. QUIC Summary

Id	Parameter	Description
1	Abstract of Model Capabilities	<p>QUIC (Quick Urban & Industrial Complex) Dispersion Modeling System</p> <p>QUIC is composed of several sub-models to produce atmospheric dispersion results. The three basic components are QUIC-URB, QUIC-PLUME, and QUIC-GUI.</p> <p>QUIC-URB produces a realistic 3D wind field around buildings and other flow obstructions using a diagnostic set of empirical relationships.</p> <p>QUIC-PLUME is a Lagrangian dispersion model that uses the mean wind fields from QUIC-URB and turbulence from a customized Langevin random walk within the QUIC-PLUME model.</p> <p>QUIC-GUI is a user interface for developing model input and viewing model output.</p> <p>QUIC is a fast response model that produces reasonably accurate results that account for buildings and vegetation.</p>
2	Model Developer	<p>Los Alamos National Laboratory. Funding sources include the Department of Energy Chemical Biological Non-Proliferation Program, National Nuclear Security Administration, Department of Homeland Security Science and Technology, and the Defense Threat Reduction Agency.</p>
3	Availability	<p>Freely available for government use from Los Alamos National Laboratory with completion of a government use license. http://www.lanl.gov/projects/quic/index.shtml</p>
4	Model Description	<p>QUIC is a fast response dispersion model that is composed of several sub-models to produce realistic wind and concentration fields. This model was developed over the last 15 years, primarily in response to urban threats of chemical or biological releases. The goal of QUIC is to provide fast-running simulations with building effects incorporated for emergency planners and emergency response personnel.</p> <p>QUIC-URB is the wind model that is used to quickly produce realistic wind fields. It uses empirical equations following Röckle (1990), with additional improvements, to create 3D wind fields that account for building obstructions, trees, and terrain. Alternatively, QUIC also contains a simplified computational fluid dynamics (CFD) code called QUIC-CFD. This model takes significantly more time to compute the wind field compared with QUIC-URB, but produces more realistic wind fields. Since it is a simplified CFD model, it produces a solution faster than a full CFD solution.</p> <p>QUIC-PLUME is the Lagrangian dispersion model that uses the 3D wind field from QUIC-URB or QUIC-CFD to produce the concentration field. Due to the nature of turbulence around buildings, a customized Langevin random walk code is used. The user specifies the number of particles, which represents the release compound, to include in the simulation. The greater the number of particles, the greater the accuracy of the result. However, more particles also requires a longer computational time. Surface deposition or surface reflection is available.</p> <p>QUIC-GUI is the graphical user interface, which allows users to visualize the wind vectors, streamlines, velocity profiles, concentration contours, deposition contours, etc.</p> <p>Additional models, such as PRESSURE, which allows users to plot pressure contours and POPULATION, which estimates exposures to population based on the georeferenced domain and the daytime/nighttime populations in the lower 48 states are available in QUIC.</p>

Table C.3 (cont.)

Id	Parameter	Description
5	Intended Application(s)	QUIC is designed for use in a variety of emergency response and planning scenarios in which a contaminant is released in a built-up environment, such as urban and suburban areas, and for particulate, dense gas, and neutral gas releases.
6	Strengths and Weaknesses	<p>Strengths: Quickly generates realistic wind fields, accounting for physical obstructions in the environment, without the cost associated with CFD. The dispersion results may be used in both near-field and far-field applications.</p> <p>Weaknesses: Results are not as accurate as CFD.</p>
7	Model Inputs	<p>Source:</p> <ul style="list-style-type: none"> • Both neutrally buoyant and dense gas releases, as well as particulate releases, liquid pools, bio-slurry, and two-phase releases are available. • An artificial agent library is supplied with QUIC; an actual agent library with actual agent properties (Official Use Only) is also available. • Both continuous and instantaneous releases are possible, and the geometry of the release may be prescribed as a sphere, line, cylinder, area, volume, moving point, or submunitions (small projectiles impacting a target). <p>Flow Obstructions:</p> <ul style="list-style-type: none"> • Buildings may be input manually or imported from a ShapeFile. • QUIC can handle regular, rectangular buildings, as well as compound-buildings and footprints of any polygon or ellipse. • Vegetation, which is treated as a porous obstacle, can also be added as rectangles, polygon, or ellipses. • Parking garages and bridges are also under development. <p>Meteorology:</p> <ul style="list-style-type: none"> • Wind speed profiles (logarithmic, power-law, urban canopy, or user-defined) are input to the Met Generator. Wind direction profiles and roughness length are also available inputs. The model can accommodate multiple profiles at different measurement locations. • In addition to manual input into the GUI, profile data may be imported from a delimited text file. • Wind fields from a mesoscale model is another option available for defining the model meteorology. WRF, MM5, and HOTMAC output are available options. • Atmospheric stability can be prescribed by inverse Monin-Obukhov length.
8	Model Outputs	<p>Users can save data in ASCII, MAT, or ArcGIS format, with the ability to save data from X, Y, or Z profiles, or planes through the domain.</p> <p>Users can also save specific receptor data, as well as JPG files of plots created within QUIC.</p>
9	Model Validation	<p>Data visualization is available through the QUIC-GUI module.</p> <p>The QUIC model has been applied for a variety of urban dispersion cases, and model developers have evaluated and improved the code over the years using both wind tunnel and field experiment data. Evaluation datasets include:</p> <ul style="list-style-type: none"> • Salt Lake City 2000 • Joint Urban 2003 (Oklahoma City) • Urban Dispersion Program 2005 (Midtown Manhattan, New York City)

Table C.3 (cont.)

Id	Parameter	Description
10	Runtime Characteristics	Varies depending on the size of the domain, number of buildings, and other model set-up parameters, but generally runs within tens of seconds for smaller domains, to tens of minutes for larger domains.
11	Computer Platform	Windows or Mac
12	Reference Document(s)	Williams MD, MJ Brown, B Singh, and D Boswell. 2004. <i>QUIC-PLUME Theory Guide</i> . LA-UR-01-0561. Los Alamos, NM. Nelson M and M. Brown. 2013. <i>The QUIC Start Guide (v 6.01): The Quick Urban & Industrial Complex (QUIC) Dispersion Modeling System</i> . LA-UR-13-27291. Los Alamos, NM.

Appendix D

CFD Model Detailed Summary Table

Appendix D - CFD Model Detailed Summary Table

Computational fluid dynamics (CFD) models simulate fluid dynamics, mass transport, and energy exchanges by numerically solving three-dimensional transient mass, momentum, and energy conservation equations. Because CFD models solve the fundamental equations, they can handle almost all terrain types, source conditions, and environmental conditions. However, because CFD models were designed for solving general fluid dynamics problems, they may lack the imbedded material database and tuned parameters for this specific application. In general, CFD models have not been rigorously evaluated for non-neutral atmospheric conditions, cases with low mixing heights, or other specific and unique meteorological conditions. Table D.1 lists the model capabilities for the four CFD software codes considered in this report.

Table D.1. Model Capability for the Four Investigated CFD Software

	CFX	Fluent	STAR-CCM+	MFIX	FDS
Model Developer	ANSYS	ANSYS	CD-adapco	National Energy Technology Laboratory (NETL)	National Institute of Standards and Technology (NIST)
Availability	Commercial	Commercial	Commercial	Open source	Open source
Multi-component gas model ¹	Y	Y	Y	Y	Y
Automatic mixed gas properties update ²	Y	Y	Y	N	Y
Solver coupling ³	Pressure-velocity fully coupled	Pressure-velocity fully coupled and segregated	Pressure-velocity fully coupled and segregated	Pressure-velocity segregated	Pressure-velocity segregated
Parallel computation	Y	Y	Y	Y (efficiency is not good)	Y
GPU acceleration ⁴	N	Y	N	N	N
Concentration convection term interpolation scheme ⁵	Blended 1st and 2nd order upwind	Blended 1st and 2nd order upwind (different chemical species using different schemes)	1st or 2nd order upwind (no blending feature)	1st or 2nd order upwind (no blending feature)	Central Difference, Godnuov, MINMOD, Superbee, CHARM, MP5

Table D.1 (cont.)

	CFX	Fluent	STAR-CCM+	MFiX	FDS
GUI	Y	Y	Y	Y (0.1 version, some parameters setups are not compatible with solver)	Y (with Blender or PyroSim)
Mesh generator	Y	Y	Y	Y	Y
Unstructured, adaptive meshing ⁶	Y (AREVA used CFX to generate the mesh for multistack farm)	Y	Y (A testing mesh was generated according to AREVA provided terrain file ⁷)	N (Cartesian grid without supporting quadtree or similar meshing technique; cannot import volume mesh from other mesh generation tool)	N (Cartesian grid)
Turbulence model	RANS: zero equation; k-epsilon; k-omega; SST; Reynolds stress; and several modified models; large eddy simulation (LES); detached eddy simulation (DES)	RANS: Spalart-Allmaras; k-epsilon; k-omega; SST; Reynolds stress; and several modified models; LES; DES	RANS: zero equation; k-epsilon; k-omega; SST; Reynolds stress; and several modified models; LES; DES	RANS: K-epsilon	LES
Price ⁸	\$\$\$\$\$	\$\$\$\$\$	\$\$\$	\$0	\$0

Notes:

- All of the models solve these equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = \sum_{n=1}^N R_n \quad (\text{D.1})$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j u_i) = \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + f_i + \rho g_i \quad (\text{D.2})$$

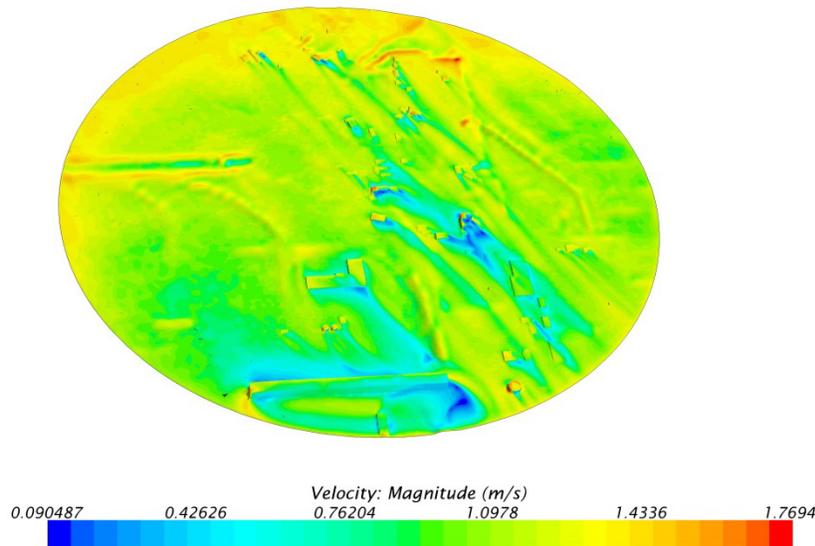
$$\frac{\partial X_n}{\partial t} + \frac{\partial}{\partial x_i} (u_i X_n) = \frac{\partial}{\partial x_i} \left(D_n \frac{\partial X_n}{\partial x_i} \right) + \frac{R_n}{\rho} \quad (\text{D.3})$$

where ρ : density; u_i : velocity; R_n : gas source/sink term; P : pressure; g_i : gravity acceleration; D_n : diffusion coefficient; X_n : gas component weight fraction.

2. This is not necessary for diluted gas dissipation.
3. CFX focuses on the fully coupled solver. Fluent, STAR-CCM+, and MFiX focus on the segregated solver. Fluent and STAR-CCM+ provide the option of enabling fully coupled solver. FDS uses a segregated procedure to solve all the equations. In the FDS Technical Reference Guide, this is called the explicit second-order predictor/corrector scheme.
4. Only Fluent supports GPU acceleration. It was claimed that technique/hardware can speed up the calculation by 2 to 3 times. However, because of the limited amount of GPU memory (up to 24 GB), the accelerated problem cannot be very complicated. Additionally, not all of the models or solvers can benefit from GPU acceleration.
5. In the simulation test for the bench-scale experiment, the pure second-order upwind scheme causes some error and instability. If the blended feature is not available (STAR-CCM+ and MFiX), the user can only choose the first order upwind scheme to get a temporary solution first, and use the second order scheme to continue the iteration to get a more accurate solution. This is good for steady-state simulation, but not convenient for transient simulation. FDS provides more options for the interpolation scheme to balance the choices of solution accuracy and simulation stability.

Unstructured and adaptive meshing is a critical feature for tank farm CFD modeling. Therefore, MFiX is not suitable for tank-farm-scale applications. The open source code FDS only supports structured Cartesian mesh and subdomain refinement, so the solid objects in FDS simulation are approximated by cuboids. For efficient implementation of the approximation for complicated geometry, there are two tools: Blender FDS and PyroSim can help convert CAD geometries into the FDS input file.

6. Mesh test:



Flow simulation in STAR-CCM+ for a multi-stack tank farm. This is only a quick test with 1.5 million mesh cells. In AREVA’s report, they used 95 and 121 million mesh cells for the simulation in CFX.

7. Price may vary because of the total purchased number of licenses and/or purchasing options. Generally, the licenses can be purchased per year, job run, and hour.

The following describes an example simulation for the FDS code, and the results are compared with those from STAR-CCM+ and with QUIC as reported in Flaherty et al (2016).

Figure D.1(a) shows a satellite picture from Google Maps for the bench-scale test area. Because the satellite image has not been updated recently, a new building (3820) is missing, so a PNNL internal buildings map is shown in Figure D.1(b). The red dot on the map is the approximate location of the releasing point, the blue triangle is the location of sensor MR3011, the purple triangle is the location of Gastronics G2, and the orange square is the tower for record meteorological data.

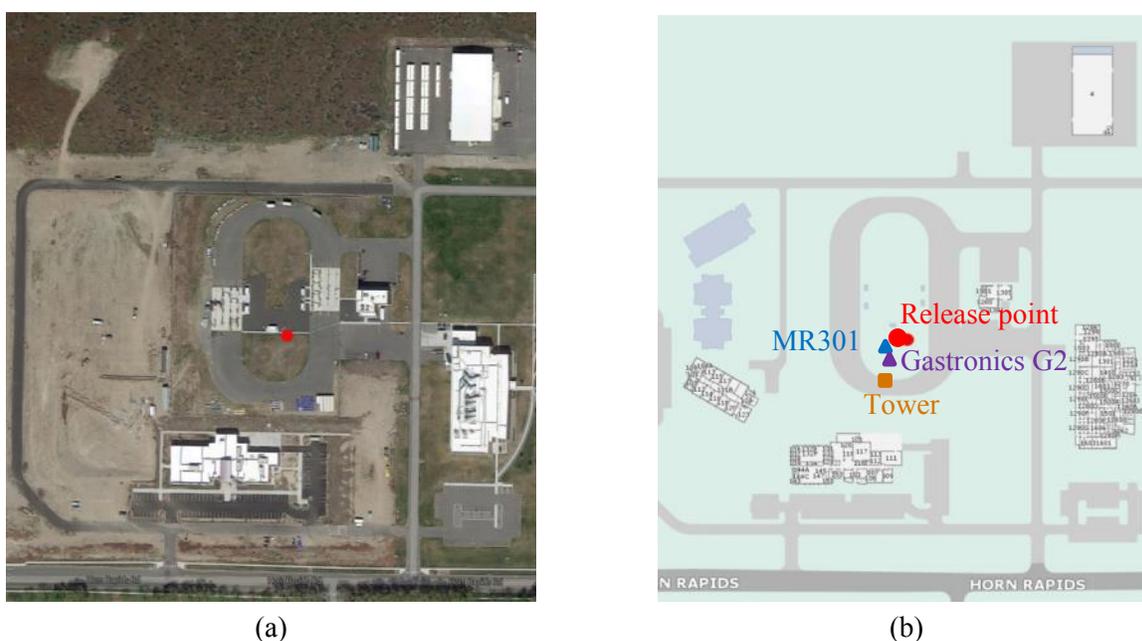


Figure D.1. (a) Satellite picture for bench-scale test area and (b) PNNL internal buildings map for the bench-scale test area. The red dot is the approximate location of releasing point, the blue triangle is the location of sensor MR3011, the purple triangle is the location of Gastronics G2, and the orange square is the tower for record meteorological data.

QUIC, STAR-CCM+, and FDS were used to estimate the concentration distribution from a gas release test. The release started on May 13, 2016, at 15:52, and ended on May 13, 2016, at 16:08. Three gases were released together. The flow rate for the C_4H_8 was 100L/min, NH_3 was 100L/min, and N_2O was 99.9L/min. The concentrations in the gas cylinder were 5%, 4.9%, and 2% respectively. Therefore, the releasing rate is 0.191 g/s, 0.057 g/s, and 0.060 g/s. Figure D.2(a) and (b) show the wind speed and wind direction measured at the tower. Figure D.2(c) shows the wind vectors to provide a better understanding of the wind fluctuation during the release period. The red vector is the median direction and speed, which are 4.917 m/s and 37.06 deg. QUIC and STAR-CCM+ used this median direction and speed as the boundary condition to develop the steady wind field. FDS used the original meteorological data shown in Figure D.2(a) and (b) as desired wind velocity, and developed the time varying dynamic wind field by data assimilation method integrated in FDS. Figure D.3 shows the comparison between modeling predictions and bench-scale test measurements at sensor MR3011 and Gastronics G2. Note that the sensors did not capture N_2O concentration during the bench-scale test, so only C_4H_8 and NH_3 were used for comparisons. Generally, STAR-CCM+ can capture the correct magnitude of the concentration of the released gas. FDS used the real meteorological data to build the dynamic wind field, so FDS predictions have strong fluctuations, which are similar to the measurements. QUIC underestimated the concentration. This does not mean QUIC is not good for this application. Because the sensors are located very close to

the source, a small bias of the flow direction near source can make the concentration at sensor change considerably.

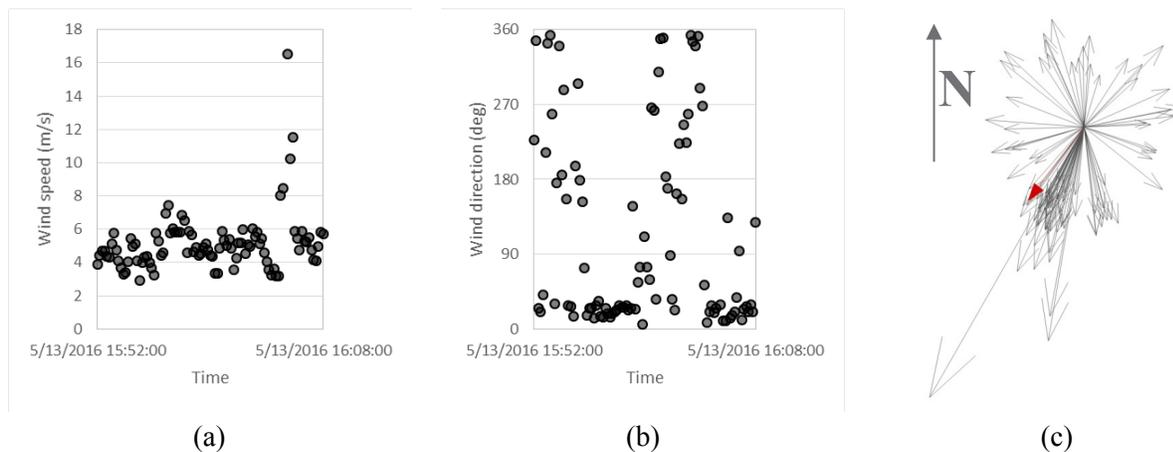


Figure D.2. Wind speed and direction from May 13, 2016, at 15:52 to May 13, 2016, at 16:08: (a) wind speed; (b) wind direction; (c) wind vectors.

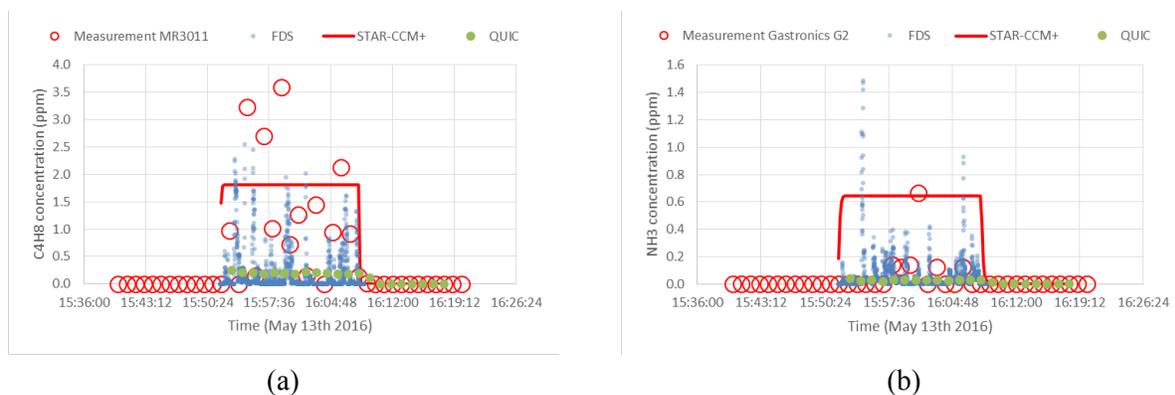


Figure D.3. Comparison between CFD modeling and bench-scale test measurement: (a) C_4H_8 concentration at sensor MR3011; (b) NH_3 at sensor Gastronics G2.

References

Flaherty JE, EC Golovich, RR Kirkham, TL Stewart, TM Brouns, KB Olsen, JL Downs, JN Thomle, and C Arimescu. 2016. *Bench-Scale Testing of the Vapor Monitoring and Detection System*. PNNL-25892, Pacific Northwest National Laboratory, Richland, WA.

Appendix E

Real-Time Model Ranking

Appendix E - Real-Time Model Ranking

Table E.1. Real-Time Model Ranking for APGEMS and CALPUFF

Attribute	Weight (0-2)	APGEMS Score (0-2)	Weighted Model Score	CALPUFF Score (0-2)	Weighted Model Score
Release Height					
Ground level release	2	2	4	2	4
Elevated release	2	1	2	1	2
Thermally buoyant	1	1	1	1	1
Momentum	1	1	1	1	1
Release Type					
Gas	2	2	4	2	4
Particles	0	1	0	1	0
Source Type(s)					
Point	2	1	2	2	4
Area	1	1	1	1	1
Volume	1	0	0	1	1
Line	0	0	0	1	0
Models multiple sources	1	0	0	2	2
Meteorological Inputs					
Time Varying	1	1	1	2	2
Spatially Varying	1	1	1	2	2
Real Time Meteorology	2	2	4	0	0
Historical Meteorology	1	1	1	2	2
Treatment of Specific or Unique Conditions					
Inversion Layer	1	1	1	2	2
Fumigation	1	1	1	1	1
Low Wind Speed	2	0	0	2	4
Building Wake	2	1	2	1	2
Stack-tip Downwash	2	1	2	1	2
Dry deposition	0	1	0	2	0
Wet deposition	0	1	0	2	0
Terrain Capability					
Uneven terrain	2	2	4	2	4
Terrain steering	1	2	2	2	2

Table E.1 (cont.)

Attribute	Weight (0-2)	APGEMS Score (0-2)	Weighted Model Score	CALPUFF Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	1	1	1	1	1
Polar Grid	1	1	1	1	1
Applicable Distance(s)					
≤ 100 m of release	2	1	2	1	2
100 m to 15,000 m	1	2	2	1	1
15,000 m to 50,000 m	0	1	0	2	0
≥ 50,000 m	0	0	0	2	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	1	0	1	0
Output Type(s)					
Text	2	1	2	2	4
Chart	1	0	0	0	0
Contour Plots	1	1	1	1	1
Time Averages					
≤ 1 minute	2	0	0	0	0
> 1 minute	1	1	1	1	1
Usability					
User Interface	2	2	4	1	2
Ease of Use	2	2	4	1	2
Validation / Accuracy / Vetting of methods	2	1	2	2	4
Runtime					
Fast Setup	2	2	4	1	2
Fast Execution	2	2	4	1	2
Maximum Score:	110	TOTAL:	66	TOTAL:	70

Table E.2. Real-Time Model Ranking for ALOHA and EPIcode

Attribute		Weight (0-2)	ALOHA Score (0-2)	Weighted Model Score	EPIcode Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	1	2	1	2
Thermally buoyant		1	0	0	1	1
Momentum		1	1	1	1	1
Release Type						
Gas		2	2	4	2	4
Particles		0	0	0	1	0
Source Type(s)						
Point		2	1	2	1	2
Area		1	1	1	2	2
Volume		1	1	1	1	1
Line		0	0	0	2	0
Models multiple sources		1	0	0	0	0
Meteorological Inputs						
Time Varying		1	0	0	0	0
Spatially Varying		1	0	0	0	0
Real Time Meteorology		2	0	0	0	0
Historical Meteorology		1	0	0	0	0
Treatment of Specific or Unique Conditions						
Inversion Layer		1	1	1	1	1
Fumigation		1	0	0	0	0
Low Wind Speed		2	0	0	1	2
Building Wake		2	1	2	0	0
Stack-tip Downwash		2	0	0	0	0
Dry deposition		0	0	0	1	0
Wet deposition		0	0	0	0	0
Terrain Capability						
Uneven terrain		2	0	0	0	0
Terrain steering		1	0	0	0	0

Table E.2 (cont.)

Attribute	Weight (0-2)	ALOHA Score (0-2)	Weighted Model Score	EPICode Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	1	0	0	0	0
Polar Grid	1	0	0	0	0
Applicable Distance(s)					
≤ 100 m of release	2	1	2	0	0
100 m to 15,000 m	1	1	1	1	1
15,000 m to 50,000 m	0	1	0	1	0
≥ 50,000 m	0	1	0	1	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	0	0	0	0
Output Type(s)					
Text	2	1	2	1	2
Chart	1	1	1	1	1
Contour Plots	1	0	0	1	1
Time Averages					
≤ 1 minute	2	0	0	0	0
> 1 minute	1	1	1	1	1
Usability					
User Interface	2	2	4	2	4
Ease of Use	2	2	4	2	4
Validation / Accuracy / Vetting of methods	2	2	4	2	4
Runtime					
Fast Setup	2	2	4	2	4
Fast Execution	2	2	4	2	4
Maximum Score:	110	TOTAL:	49	TOTAL:	50

Table E.3. Real-Time Model Ranking for SAFER and HYSPLIT

Attribute		Weight (0-2)	SAFER Score (0-2)	Weighted Model Score	HYSPLIT Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	1	2	1	2
Thermally buoyant		1	1	1	1	1
Momentum		1	1	1	0	0
Release Type						
Gas		2	2	4	2	4
Particles		0	1	0	2	0
Source Type(s)						
Point		2	1	2	1	2
Area		1	1	1	1	1
Volume		1	1	1	0	0
Line		0	0	0	0	0
Models multiple sources		1	0	0	0	0
Meteorological Inputs						
Time Varying		1	1	1	2	2
Spatially Varying		1	1	1	2	2
Real Time Meteorology		2	1	2	2	4
Historical Meteorology		1	1	1	2	2
Treatment of Specific or Unique Conditions						
Inversion Layer		1	1	1	1	1
Fumigation		1	0	0	0	0
Low Wind Speed		2	0	0	0	0
Building Wake		2	0	0	0	0
Stack-tip Downwash		2	0	0	0	0
Dry deposition		0	1	0	1	0
Wet deposition		0	1	0	1	0
Terrain Capability						
Uneven terrain		2	0	0	1	2
Terrain steering		1	0	0	1	1

Table E.3 (cont.)

Attribute	Weight (0-2)	SAFER Score (0-2)	Weighted Model Score	HYSPLIT Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	1	0	0	1	1
Polar Grid	1	0	0	1	1
Applicable Distance(s)					
≤ 100 m of release	2	1	2	0	0
100 m to 15,000 m	1	1	1	1	1
15,000 m to 50,000 m	0	1	0	1	0
≥ 50,000 m	0	0	0	1	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	1	0	1	0
Output Type(s)					
Text	2	1	2	1	2
Chart	1	1	1	1	1
Contour Plots	1	1	1	1	1
Time Averages					
≤ 1 minute	2	0	0	0	0
> 1 minute	1	1	1	1	1
Usability					
User Interface	2	1	2	2	4
Ease of Use	2	1	2	2	4
Validation / Accuracy / Vetting of methods	2	1	2	2	4
Runtime					
Fast Setup	2	1	2	2	4
Fast Execution	2	1	2	2	4
Maximum Score:	110	TOTAL: 44		TOTAL: 60	

Table E.4. Real-Time Model Ranking for ADPAT/LODI and QUIC

Attribute		Weight (0-2)	ADAPT/LODI Score (0-2)	Weighted Model Score	QUIC Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	1	2	2	4
Thermally buoyant		1	1	1	1	1
Momentum		1	1	1	1	1
Release Type						
Gas		2	2	4	2	4
Particles		0	1	0	2	0
Source Type(s)						
Point		2	1	2	1	2
Area		1	1	1	1	1
Volume		1	1	1	1	1
Line		0	0	0	1	0
Models multiple sources		1	0	0	2	2
Meteorological Inputs						
Time Varying		1	2	2	1	1
Spatially Varying		1	2	2	1	1
Real Time Meteorology		2	2	4	0	0
Historical Meteorology		1	1	1	1	1
Treatment of Specific or Unique Conditions						
Inversion Layer		1	0	0	1	1
Fumigation		1	0	0	1	1
Low Wind Speed		2	0	0	1	2
Building Wake		2	0	0	2	4
Stack-tip Downwash		2	0	0	1	2
Dry deposition		0	1	0	1	0
Wet deposition		0	0	0	1	0
Terrain Capability						
Uneven terrain		2	1	2	1	2
Terrain steering		1	1	1	1	1

Table E.4 (cont.)

Attribute	Weight (0-2)	ADAPT/LODI Score (0-2)	Weighted Model Score	QUIC Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	1	1	1	1	1
Polar Grid	1	1	1	1	1
Applicable Distance(s)					
≤ 100 m of release	2	0	0	2	4
100 m to 15,000 m	1	1	1	1	1
15,000 m to 50,000 m	0	1	0	1	0
≥ 50,000 m	0	1	0	0	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	1	0	1	0
Output Type(s)					
Text	2	1	2	1	2
Chart	1	1	1	1	1
Contour Plots	1	1	1	1	1
Time Averages					
≤ 1 minute	2	0	0	2	4
> 1 minute	1	1	1	1	1
Usability					
User Interface	2	2	4	1	2
Ease of Use	2	2	4	1	2
Validation / Accuracy / Vetting of methods	2	2	4	1	2
Runtime					
Fast Setup	2	2	4	1	2
Fast Execution	2	2	4	1	2
Maximum Score:	110	TOTAL:	60	TOTAL:	66

Appendix F

Worker Safety and Emergency Planning Model Ranking

Appendix F – Worker Safety and Emergency Planning Model Ranking

Table F.1. Worker Safety and Emergency Planning Model Ranking for APGEMS and CALPUFF

Attribute	Weight (0-2)	APGEMS Score (0-2)	Weighted Model Score	CALPUFF Score (0-2)	Weighted Model Score
Release Height					
Ground level release	2	2	4	2	4
Elevated release	2	1	2	1	2
Thermally buoyant	1	1	1	1	1
Momentum	1	1	1	1	1
Release Type					
Gas	2	2	4	2	4
Particles	0	1	0	1	0
Source Type(s)					
Point	2	1	2	2	4
Area	1	1	1	1	1
Volume	1	0	0	1	1
Line	0	0	0	1	0
Models multiple sources	1	0	0	2	2
Meteorological Inputs					
Time Varying	1	1	1	2	2
Spatially Varying	1	1	1	2	2
Real Time Meteorology	0	2	0	0	0
Historical Meteorology	2	1	2	2	4
Treatment of Specific or Unique Conditions					
Inversion Layer	1	1	1	2	2
Fumigation	1	1	1	1	1
Low Wind Speed	2	0	0	2	4
Building Wake	2	1	2	1	2
Stack-tip Downwash	2	1	2	1	2
Dry deposition	0	1	0	2	0
Wet deposition	0	1	0	2	0
Terrain Capability					
Uneven terrain	2	2	4	2	4
Terrain steering	1	2	2	2	2

Table F.1 (cont.)

Attribute	Weight (0-2)	APGEMS Score (0-2)	Weighted Model Score	CALPUFF Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	1	1	1	1	1
Polar Grid	1	1	1	1	1
Applicable Distance(s)					
≤ 100 m of release	2	0	0	1	2
100 m to 15,000 m	1	1	1	1	1
15,000 m to 50,000 m	0	1	0	2	0
≥ 50,000 m	0	0	0	2	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	1	0	1	0
Output Type(s)					
Text	2	1	2	2	4
Chart	1	0	0	0	0
Contour Plots	1	1	1	1	1
Time Averages					
≤ 1 minute	2	0	0	0	0
> 1 minute	1	1	1	1	1
Usability					
User Interface	1	2	2	1	1
Ease of Use	1	2	2	1	1
Validation / Accuracy / Vetting of methods	2	1	2	2	4
Runtime					
Fast Setup	1	2	2	0	0
Fast Execution	1	2	2	1	1
Maximum Score:	100	TOTAL:	52	TOTAL:	67

Table F.2. Worker Safety and Emergency Planning Model Ranking for ALOHA and EPIcode

Attribute		Weight (0-2)	ALOHA Score (0-2)	Weighted Model Score	EPIcode Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	1	2	1	2
Thermally buoyant		1	0	0	1	1
Momentum		1	1	1	1	1
Release Type						
Gas		2	2	4	2	4
Particles		0	0	0	1	0
Source Type(s)						
Point		2	1	2	1	2
Area		1	1	1	2	2
Volume		1	1	1	1	1
Line		0	0	0	2	0
Models multiple sources		1	0	0	0	0
Meteorological Inputs						
Time Varying		1	0	0	0	0
Spatially Varying		1	0	0	0	0
Real Time Meteorology		0	0	0	0	0
Historical Meteorology		2	0	0	0	0
Treatment of Specific or Unique Conditions						
Inversion Layer		1	1	1	1	1
Fumigation		1	0	0	0	0
Low Wind Speed		2	0	0	1	2
Building Wake		2	1	2	0	0
Stack-tip Downwash		2	0	0	0	0
Dry deposition		0	0	0	1	0
Wet deposition		0	0	0	0	0
Terrain Capability						
Uneven terrain		2	0	0	0	0
Terrain steering		1	0	0	0	0

Table F.2 (cont.)

Attribute	Weight (0-2)	ALOHA Score (0-2)	Weighted Model Score	EPICode Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	1	0	0	0	0
Polar Grid	1	0	0	0	0
Applicable Distance(s)					
≤ 100 m of release	2	1	2	0	0
100 m to 15,000 m	1	1	1	1	1
15,000 m to 50,000 m	0	1	0	1	0
≥ 50,000 m	0	1	0	1	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	0	0	0	0
Output Type(s)					
Text	2	1	2	1	2
Chart	1	1	1	1	1
Contour Plots	1	0	0	1	1
Time Averages					
≤ 1 minute	2	0	0	0	0
> 1 minute	1	1	1	1	1
Usability					
User Interface	1	2	2	2	2
Ease of Use	1	2	2	2	2
Validation / Accuracy / Vetting of methods	2	2	4	2	4
Runtime					
Fast Setup	1	2	2	2	2
Fast Execution	1	2	2	2	2
Maximum Score:	100	TOTAL:	41	TOTAL:	42

Table F.3. Worker Safety and Emergency Planning Model Ranking for SAFER and ARCON86

Attribute		Weight (0-2)	SAFER Score (0-2)	Weighted Model Score	ARCON96 Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	1	2	1	2
Thermally buoyant		1	1	1	0	0
Momentum		1	1	1	1	1
Release Type						
Gas		2	2	4	2	4
Particles		0	1	0	0	0
Source Type(s)						
Point		2	1	2	1	2
Area		1	1	1	1	1
Volume		1	1	1	0	0
Line		0	0	0	0	0
Models multiple sources		1	0	0	0	0
Meteorological Inputs						
Time Varying		1	1	1	1	1
Spatially Varying		1	1	1	0	0
Real Time Meteorology		0	1	0	1	0
Historical Meteorology		2	1	2	1	2
Treatment of Specific or Unique Conditions						
Inversion Layer		1	1	1	0	0
Fumigation		1	0	0	0	0
Low Wind Speed		2	0	0	2	4
Building Wake		2	0	0	2	4
Stack-tip Downwash		2	0	0	0	0
Dry deposition		0	1	0	0	0
Wet deposition		0	1	0	0	0
Terrain Capability						
Uneven terrain		2	0	0	1	2
Terrain steering		1	0	0	0	0

Table F.3 (cont.)

Attribute	Weight (0-2)	SAFER Score (0-2)	Weighted Model Score	ARCON96 Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	1	0	0	0	0
Polar Grid	1	0	0	0	0
Applicable Distance(s)					
≤ 100 m of release	2	1	2	2	4
100 m to 15,000 m	1	1	1	1	1
15,000 m to 50,000 m	0	1	0	1	0
≥ 50,000 m	0	0	0	0	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	1	0	0	0
Output Type(s)					
Text	2	1	2	2	4
Chart	1	1	1	0	0
Contour Plots	1	1	1	0	0
Time Averages					
≤ 1 minute	2	0	0	0	0
> 1 minute	1	1	1	1	1
Usability					
User Interface	1	1	1	1	1
Ease of Use	1	1	1	2	2
Validation / Accuracy / Vetting of methods	2	1	2	2	4
Runtime					
Fast Setup	1	1	1	1	1
Fast Execution	1	1	1	2	2
Maximum Score:	100	TOTAL:	39	TOTAL:	51

Table F.4. Worker Safety and Emergency Planning Model Ranking for AIHA-Eddy and AIHA-Plume

Attribute	Weight (0-2)	AIHA-Eddy Score (0-2)	Weighted Model Score	AIHA-Plume Score (0-2)	Weighted Model Score
Release Height					
Ground level release	2	2	4	2	4
Elevated release	2	1	2	0	0
Thermally buoyant	1	0	0	0	0
Momentum	1	0	0	0	0
Release Type					
Gas	2	2	4	2	4
Particles	0	0	0	0	0
Source Type(s)					
Point	2	2	4	1	2
Area	1	0	0	0	0
Volume	1	0	0	0	0
Line	0	0	0	0	0
Models multiple sources	1	0	0	0	0
Meteorological Inputs					
Time Varying	1	0	0	0	0
Spatially Varying	1	0	0	0	0
Real Time Meteorology	0	1	0	1	0
Historical Meteorology	2	2	4	2	4
Treatment of Specific or Unique Conditions					
Inversion Layer	1	0	0	0	0
Fumigation	1	0	0	0	0
Low Wind Speed	2	0	0	0	0
Building Wake	2	0	0	0	0
Stack-tip Downwash	2	0	0	0	0
Dry deposition	0	0	0	0	0
Wet deposition	0	0	0	0	0
Terrain Capability					
Uneven terrain	2	0	0	0	0
Terrain steering	1	0	0	0	0

Table F.4 (cont.)

Attribute	Weight (0-2)	AIHA-Eddy Score (0-2)	Weighted Model Score	AIHA-Plume Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	1	0	0	0	0
Polar Grid	1	0	0	0	0
Applicable Distance(s)					
≤ 100 m of release	2	2	4	1	2
100 m to 15,000 m	1	0	0	0	0
15,000 m to 50,000 m	0	0	0	0	0
≥ 50,000 m	0	0	0	0	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	0	0	0	0
Output Type(s)					
Text	2	1	2	1	2
Chart	1	1	1	1	1
Contour Plots	1	0	0	0	0
Time Averages					
≤ 1 minute	2	2	4	0	0
> 1 minute	1	1	1	1	1
Usability					
User Interface	1	2	2	2	2
Ease of Use	1	2	2	2	2
Validation / Accuracy / Vetting of methods	2	1	2	0	0
Runtime					
Fast Setup	1	2	2	2	2
Fast Execution	1	2	2	2	2
Maximum Score:	100	TOTAL:	44	TOTAL:	32

Table F.5. Worker Safety and Emergency Planning Model Ranking for QUIC and FDS

Attribute		Weight (0-2)	QUIC Score (0-2)	Weighted Model Score	FDS Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	2	4	2	4
Thermally buoyant		1	1	1	1	1
Momentum		1	1	1	1	1
Release Type						
Gas		2	2	4	2	4
Particles		0	2	0	2	0
Source Type(s)						
Point		2	1	2	1	2
Area		1	1	1	2	2
Volume		1	1	1	2	2
Line		0	1	0	1	0
Models multiple sources		1	2	2	2	2
Meteorological Inputs						
Time Varying		1	1	1	2	2
Spatially Varying		1	1	1	1	1
Real Time Meteorology		0	0	0	0	0
Historical Meteorology		2	1	2	2	4
Treatment of Specific or Unique Conditions						
Inversion Layer		1	1	1	1	1
Fumigation		1	1	1	1	1
Low Wind Speed		2	1	2	2	4
Building Wake		2	2	4	2	4
Stack-tip Downwash		2	1	2	2	4
Dry deposition		0	1	0	1	0
Wet deposition		0	1	0	1	0
Terrain Capability						
Uneven terrain		2	1	2	1	2
Terrain steering		1	1	1	1	1

Table F.4 (cont.)

Attribute		Weight (0-2)	QUIC Score (0-2)	Weighted Model Score	FDS Score (0-2)	Weighted Model Score
Receptor Types						
Discrete		2	1	2	1	2
Cartesian Grid		1	1	1	1	1
Polar Grid		1	1	1	1	1
Applicable Distance(s)						
≤ 100 m of release		2	2	4	2	4
100 m to 15,000 m		1	1	1	1	1
15,000 m to 50,000 m		0	1	0	0	0
≥ 50,000 m		0	0	0	0	0
Outputs						
Air Concentration		2	1	2	2	4
Ground Deposition		0	1	0	1	0
Output Type(s)						
Text		2	1	2	2	4
Chart		1	1	1	2	2
Contour Plots		1	1	1	2	2
Time Averages						
≤ 1 minute		2	2	4	2	4
> 1 minute		1	1	1	2	2
Usability						
User Interface		1	1	1	1	1
Ease of Use		1	1	1	1	1
Validation / Accuracy / Vetting of methods		2	1	2	1	2
Runtime						
Fast Setup		1	1	1	1	1
Fast Execution		1	1	1	1	1
Maximum Score:		100	TOTAL:	63	TOTAL:	79

Appendix G

Regulatory Model Ranking

Appendix G - Regulatory Model Ranking

Table G.1. Regulatory Model Ranking for AERMOD and ISC

Attribute	Weight (0-2)	AERMOD Score (0-2)	Weighted Model Score	ISC Score (0-2)	Weighted Model Score
Release Height					
Ground level release	2	2	4	2	4
Elevated release	2	1	2	1	2
Thermally buoyant	2	1	2	1	2
Momentum	2	1	2	1	2
Release Type					
Gas	2	2	4	2	4
Particles	1	1	1	1	1
Source Type(s)					
Point	2	2	4	2	4
Area	2	1	2	1	2
Volume	2	1	2	1	2
Line	1	1	1	1	1
Models multiple sources	2	2	4	2	4
Meteorological Inputs					
Time Varying	2	2	4	2	4
Spatially Varying	1	0	0	0	0
Real Time Meteorology	0	1	0	1	0
Historical Meteorology	2	2	4	2	4
Treatment of Specific or Unique Conditions					
Inversion Layer	2	2	4	2	4
Fumigation	1	1	1	1	1
Low Wind Speed	2	1	2	0	0
Building Wake	2	2	4	2	4
Stack-tip Downwash	2	1	2	1	2
Dry deposition	0	2	0	2	0
Wet deposition	0	2	0	2	0
Terrain Capability					
Uneven terrain	2	2	4	2	4
Terrain steering	1	1	1	1	1

Table G.1 (cont.)

Attribute	Weight (0-2)	AERMOD Score (0-2)	Weighted Model Score	ISC Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	2	1	2	1	2
Polar Grid	1	1	1	1	1
Applicable Distance(s)					
≤ 100 m of release	2	1	2	1	2
100 m to 50,000 m	2	2	4	2	4
≥ 50,000 m	0	0	0	0	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	1	0	1	0
Output Type(s)					
Text	2	2	4	2	4
Chart	1	0	0	0	0
Contour Plots	1	1	1	1	1
Time Averages					
< 1 hour	0	0	0	0	0
≥ 1 hour	2	2	4	2	4
Usability					
User Interface	1	1	1	1	1
Ease of Use	1	1	1	1	1
Validation / Accuracy / Vetting of methods	2	2	4	2	4
Runtime					
Fast Setup	1	1	1	1	1
Fast Execution	1	1	1	1	1
Maximum Score:	120	TOTAL:	84	TOTAL:	82

Table G.2. Regulatory Model Ranking for CALPUFF and SCIPUFF

Attribute		Weight (0-2)	CALPUFF Score (0-2)	Weighted Model Score	SCIPUFF Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	1	2	1	2
Thermally buoyant		2	1	2	1	2
Momentum		2	1	2	1	2
Release Type						
Gas		2	2	4	2	4
Particles		1	1	1	1	1
Source Type(s)						
Point		2	2	4	2	4
Area		2	1	2	1	2
Volume		2	1	2	1	2
Line		1	1	1	0	0
Models multiple sources		2	2	4	2	4
Meteorological Inputs						
Time Varying		2	2	4	2	4
Spatially Varying		1	2	2	2	2
Real Time Meteorology		0	0	0	0	0
Historical Meteorology		2	2	4	2	4
Treatment of Specific or Unique Conditions						
Inversion Layer		2	2	4	2	4
Fumigation		1	1	1	1	1
Low Wind Speed		2	2	4	2	4
Building Wake		2	1	2	0	0
Stack-tip Downwash		2	1	2	0	0
Dry deposition		0	2	0	2	0
Wet deposition		0	2	0	2	0
Terrain Capability						
Uneven terrain		2	2	4	2	4
Terrain steering		1	2	2	2	2

Table G.2 (cont.)

Attribute	Weight (0-2)	CALPUFF Score (0-2)	Weighted Model Score	SCIPUFF Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	2	1	2	1	2
Cartesian Grid	2	1	2	1	2
Polar Grid	1	1	1	1	1
Applicable Distance(s)					
≤ 100 m of release	2	1	2	1	2
100 m to 50,000 m	2	2	4	2	4
≥ 50,000 m	0	2	0	2	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	1	0	1	0
Output Type(s)					
Text	2	2	4	1	2
Chart	1	0	0	1	1
Contour Plots	1	1	1	1	1
Time Averages					
< 1 hour	0	0	0	1	0
≥ 1 hour	2	2	4	2	4
Usability					
User Interface	1	1	1	1	1
Ease of Use	1	1	1	1	1
Validation / Accuracy / Vetting of methods	2	2	4	2	4
Runtime					
Fast Setup	1	0	0	1	1
Fast Execution	1	1	1	1	1
Maximum Score:	120	TOTAL:	86	TOTAL:	81

Appendix H

Engineering and Research Model Ranking

Appendix H – Engineering and Research Model Ranking

Table H.1. Engineering and Research Model Ranking for Fluent, CFX, STAR-CCM+ and MFiX

Attribute		Weight (0-2)	Fluent, CFX, STAR-CCM+ Score (0-2)	Weighted Model Score	MFiX Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	2	4	2	4
Thermally buoyant		1	1	1	1	1
Momentum		1	1	1	1	1
Release Type						
Gas		2	2	4	2	4
Particles		1	2	2	2	2
Source Type(s)						
Point		2	1	2	1	2
Area		2	1	2	1	2
Volume		2	1	2	1	2
Line		1	1	1	1	1
Models multiple sources		1	2	2	2	2
Meteorological Inputs						
Time Varying		2	2	4	2	4
Spatially Varying		1	1	1	1	1
Real Time Meteorology		0	0	0	0	0
Historical Meteorology		2	1	2	1	2
Treatment of Specific or Unique Conditions						
Inversion Layer		2	1	2	1	2
Fumigation		2	1	2	1	2
Low Wind Speed		2	1	2	1	2
Building Wake		2	2	4	2	4
Stack-tip Downwash		2	2	4	2	4
Dry deposition		0	1	0	1	0
Wet deposition		0	1	0	1	0
Terrain Capability						
Uneven terrain		1	1	1	1	1
Terrain steering		1	1	1	1	1

Table H.1 (cont.)

Attribute		Weight (0-2)	Fluent, CFX, STAR-CCM+ Score (0-2)	Weighted Model Score	MFiX Score (0-2)	Weighted Model Score
Receptor Types						
Discrete		1	1	1	1	1
Cartesian Grid		1	1	1	1	1
Polar Grid		1	1	1	1	1
Applicable Distance(s)						
≤ 100 m of release		2	2	4	2	4
100 m to 15,000 m		2	2	4	1	2
15,000 m to 50,000 m		1	0	0	0	0
≥ 50,000 m		0	0	0	0	0
Outputs						
Air Concentration		2	2	4	2	4
Ground Deposition		0	1	0	1	0
Output Type(s)						
Text		2	2	4	2	4
Chart		1	2	2	2	2
Contour Plots		1	2	2	1	1
Time Averages						
≤ 1 minute		2	2	4	1	2
> 1 minute		2	2	4	1	2
Usability						
User Interface		1	2	2	1	1
Ease of Use		1	2	2	1	1
Validation / Accuracy / Vetting of methods		2	1	2	1	2
Runtime						
Fast Setup		1	1	1	1	1
Fast Execution		1	1	1	1	1
Maximum Score:		116	TOTAL:	87	TOTAL:	78

Table H.2. Engineering and Research Model Ranking for QUIC and AERMOD

Attribute		Weight (0-2)	QUIC Score (0-2)	Weighted Model Score	AERMOD Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	2	4	1	2
Thermally buoyant		1	1	1	1	1
Momentum		1	1	1	1	1
Release Type						
Gas		2	2	4	2	4
Particles		1	2	2	1	1
Source Type(s)						
Point		2	1	2	2	4
Area		2	1	2	1	2
Volume		2	1	2	1	2
Line		1	1	1	1	1
Models multiple sources		1	2	2	2	2
Meteorological Inputs						
Time Varying		2	1	2	2	4
Spatially Varying		1	1	1	0	0
Real Time Meteorology		0	0	0	1	0
Historical Meteorology		2	1	2	2	4
Treatment of Specific or Unique Conditions						
Inversion Layer		2	1	2	2	4
Fumigation		2	1	2	1	2
Low Wind Speed		2	1	2	1	2
Building Wake		2	2	4	2	4
Stack-tip Downwash		2	1	2	1	2
Dry deposition		0	1	0	2	0
Wet deposition		0	1	0	2	0
Terrain Capability						
Uneven terrain		1	1	1	2	2
Terrain steering		1	1	1	1	1

Table H.2 (cont.)

Attribute	Weight (0-2)	QUIC Score (0-2)	Weighted Model Score	AERMOD Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	1	1	1	1	1
Cartesian Grid	1	1	1	1	1
Polar Grid	1	1	1	1	1
Applicable Distance(s)					
≤ 100 m of release	2	2	4	1	2
100 m to 15,000 m	2	1	2	2	4
15,000 m to 50,000 m	1	1	1	2	2
≥ 50,000 m	0	0	0	0	0
Outputs					
Air Concentration	2	1	2	1	2
Ground Deposition	0	1	0	1	0
Output Type(s)					
Text	2	1	2	2	4
Chart	1	1	1	0	0
Contour Plots	1	1	1	1	1
Time Averages					
≤ 1 minute	2	2	4	0	0
> 1 minute	2	1	2	2	4
Usability					
User Interface	1	1	1	1	1
Ease of Use	1	1	1	1	1
Validation / Accuracy / Vetting of methods	2	1	2	2	4
Runtime					
Fast Setup	1	1	1	1	1
Fast Execution	1	1	1	1	1
Maximum Score:	116	TOTAL:	72	TOTAL:	79

Table H.3. Engineering and Research Model Ranking for ARCON96 and FDS

Attribute		Weight (0-2)	ARCON96 Score (0-2)	Weighted Model Score	FDS Score (0-2)	Weighted Model Score
Release Height						
Ground level release		2	2	4	2	4
Elevated release		2	1	2	2	4
Thermally buoyant		1	0	0	1	1
Momentum		1	1	1	1	1
Release Type						
Gas		2	2	4	2	4
Particles		1	0	0	2	2
Source Type(s)						
Point		2	2	4	1	2
Area		2	1	2	2	4
Volume		2	0	0	2	4
Line		1	0	0	1	1
Models multiple sources		1	0	0	2	2
Meteorological Inputs						
Time Varying		2	1	2	2	4
Spatially Varying		1	0	0	1	1
Real Time Meteorology		0	1	0	0	0
Historical Meteorology		2	1	2	2	4
Treatment of Specific or Unique Conditions						
Inversion Layer		2	0	0	1	2
Fumigation		2	0	0	1	2
Low Wind Speed		2	2	4	2	4
Building Wake		2	2	4	2	4
Stack-tip Downwash		2	0	0	2	4
Dry deposition		0	0	0	1	0
Wet deposition		0	0	0	1	0
Terrain Capability						
Uneven terrain		1	1	1	1	1
Terrain steering		1	0	0	1	1

Table H.3 (cont.)

Attribute	Weight (0-2)	ARCON96 Score (0-2)	Weighted Model Score	FDS Score (0-2)	Weighted Model Score
Receptor Types					
Discrete	1	1	1	1	1
Cartesian Grid	1	0	0	1	1
Polar Grid	1	0	0	1	1
Applicable Distance(s)					
≤ 100 m of release	2	2	4	2	4
100 m to 15,000 m	2	1	2	1	2
15,000 m to 50,000 m	1	1	1	0	0
≥ 50,000 m	0	0	0	0	0
Outputs					
Air Concentration	2	1	2	2	4
Ground Deposition	0	0	0	1	0
Output Type(s)					
Text	2	2	4	2	4
Chart	1	0	0	2	2
Contour Plots	1	0	0	2	2
Time Averages					
≤ 1 minute	2	0	0	2	4
> 1 minute	2	2	4	2	4
Usability					
User Interface	1	1	1	1	1
Ease of Use	1	2	2	1	1
Validation / Accuracy / Vetting of methods	2	2	4	1	2
Runtime					
Fast Setup	1	1	1	1	1
Fast Execution	1	2	2	1	1
Maximum Score:	116	TOTAL:	58	TOTAL:	91

Appendix I
Parametric Study Comparisons

Appendix I - Parametric Study Comparisons

Table I.1. ISC Meteorological File Inputs

Year	Month	Day	Hour	Wind Dir (deg)	Wind Speed (m/s)	Temp (K)	Stability	Daytime Mix Height (m)	Nighttime Mix Height (m)
90	7	1	1	90	1	293	1	3000	3000
90	7	1	2	90	1	293	2	3000	3000
90	7	1	3	90	1	293	3	3000	3000
90	7	1	4	90	1	293	4	3000	3000
90	7	1	5	90	1	293	5	3000	3000
90	7	1	6	90	1	293	6	3000	3000
90	7	1	7	90	1	293	7	3000	3000
90	7	1	8	90	3.4	293	1	3000	3000
90	7	1	9	90	3.4	293	2	3000	3000
90	7	1	10	90	3.4	293	3	3000	3000
90	7	1	11	90	3.4	293	4	3000	3000
90	7	1	12	90	3.4	293	5	3000	3000
90	7	1	13	90	3.4	293	6	3000	3000
90	7	1	14	90	3.4	293	7	3000	3000
90	7	1	15	90	10	293	3	3000	3000
90	7	1	16	90	10	293	4	3000	3000
90	7	1	17	90	10	293	5	3000	3000
90	7	1	18	90	20	293	3	3000	3000
90	7	1	19	90	20	293	4	3000	3000
90	7	1	20	90	20	293	5	3000	3000
Notes:									
Mixing heights are set to a large (3000 m) value in the ISC met file b/c mixing heights are not used as a reflective surface in the "Droppo" report.									

Table I.2. AERMOD Meteorological File Inputs

Year	Month	Day	Hour	Heat Flux (Final Estimate) W/m ²	Ustar (m/s)	W_star (Final) (m/s)	Dtheta/Dz above Daytime Mixing Height (K/m)	Daytime Mix Height (m)	Nighttime Mix Height (m)	M-O Length (m)	Surface Roughness (z0 [m])	Bowen Ratio	Albedo	Wind Speed (m/s)	Wind Dir (deg)	Height (m)	Temp (K)	Height (m)	Precip Code	Precip Amount	Relative Humidity	Pressure (mb)	Cloud Cover	Wind Speed Adj Flag
9	7	1	182	1	25.2	0.133	1.280	3000	3000	-8.5	0.15	6	0.3	1	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	2	8.3	0.119	0.885	3000	3000	-18.2	0.15	6	0.3	1	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	3	2.5	0.108	0.596	3000	3000	-44.7	0.15	6	0.3	1	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	4	0.3	0.095	0.285	3000	3000	-278.6	0.15	6	0.3	1	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	5	-0.4	0.089	-9.000	-999	3000	176.1	0.15	6	0.3	1	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	6	-0.8	0.078	-9.000	-999	3000	54.1	0.15	6	0.3	1	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	7	-0.9	0.051	-9.000	-999	3000	13.4	0.15	6	0.3	1	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	8	350.0	0.454	3.078	3000	3000	-8.5	0.15	6	0.3	3.4	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	9	326.9	0.404	3.008	3000	3000	-18.2	0.15	6	0.3	3.4	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	10	99.8	0.367	2.026	3000	3000	-44.7	0.15	6	0.3	3.4	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	11	11.0	0.324	0.971	3000	3000	-278.6	0.15	6	0.3	3.4	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	12	-14.3	0.303	-9.000	-999	3000	176.1	0.15	6	0.3	3.4	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	13	-31.1	0.265	-9.000	-999	3000	54.1	0.15	6	0.3	3.4	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	14	-33.9	0.172	-9.000	-999	3000	13.4	0.15	6	0.3	3.4	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	15	350.0	1.189	3.078	3000	3000	-44.7	0.15	6	0.3	10	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	16	350.0	1.080	3.078	3000	3000	-278.6	0.15	6	0.3	10	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	17	-65.0	0.952	-9.000	-999	3000	176.1	0.15	6	0.3	10	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	18	350.0	2.377	3.078	3000	3000	-44.7	0.15	6	0.3	20	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	19	350.0	2.160	3.078	3000	3000	-278.6	0.15	6	0.3	20	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs
9	7	1	182	20	-65.0	1.905	-9.000	-999	3000	176.1	0.15	6	0.3	20	90	10	293	10	0	-9	999	987	0	NAD-OS NoSubs

Notes:
 Heat flux, U_star, W_star, and M-O Length are calculated on tabs within this spreadsheet using the initial parametric, hourly met data values from the "Droppo" report (i.e., ISC_Met)
 Dtheta/Dz is the vertical potential temperature gradient above the daytime (convective) mixing height. This variable is set to an AERMET default value 0.005 for unstable/neutral conditions or missing (-9.000) for stable conditions.
 If a stable atmosphere, then W_star, Dtheta/Dz above daytime (convective) mixing height, and the daytime (convective) mixing height are set to missing (-9's) per the AERMET User Guide.
 Surface roughness, Bowen Ratio, and albedo are approximate values for "Desert Shrubland" and are based on lookup tables for "Desert Shrubland" in the AERMET User's Guide (Tables 4-1 through 4-3).
 NAD-OS and NoSubs are AERMET-specific flags that indicate that no ASOS wind data was used; only onsite data.

ISC Runs

Table I.3. Near Surface Vent @ 1 m³/hr Ground Level Results Using ISC

Distance (m)	ISC 1-hr Average Conc. (µg/m ³)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	46108.7	A	1.0	1.3E-05	3.90E-05	0.33
30	7554.5	A	1.0	2.1E-06	4.50E-06	0.47
100	846.6	A	1.0	2.4E-07	4.00E-07	0.59
300	93.5	A	1.0	2.6E-08	4.50E-08	0.58
1000	3.4	A	1.0	9.3E-10	4.20E-09	0.22
3000	0.2	A	1.0	6.8E-11	5.10E-10	0.13
10,000	0.1	A	1.0	2.4E-11	5.70E-11	0.42
10	74670.1	B	1.0	2.1E-05	8.70E-05	0.24
30	13522.1	B	1.0	3.8E-06	1.00E-05	0.38
100	1547.6	B	1.0	4.3E-07	9.30E-07	0.46
300	202.1	B	1.0	5.6E-08	1.00E-07	0.56
1000	18.9	B	1.0	5.2E-09	9.70E-09	0.54
3000	2.1	B	1.0	5.9E-10	1.20E-09	0.49
10,000	0.2	B	1.0	5.5E-11	1.30E-10	0.42
10	133991.2	C	1.0	3.7E-05	1.80E-04	0.21
30	28056.1	C	1.0	7.8E-06	2.20E-05	0.35
100	3386.0	C	1.0	9.4E-07	2.00E-06	0.47
300	455.8	C	1.0	1.3E-07	2.30E-07	0.55
1000	50.5	C	1.0	1.4E-08	2.30E-08	0.61
3000	6.8	C	1.0	1.9E-09	3.20E-09	0.59
10,000	0.8	C	1.0	2.1E-10	4.90E-10	0.44
10	243942.3	D	1.0	6.8E-05	3.00E-04	0.23
30	56821.4	D	1.0	1.6E-05	4.10E-05	0.38
100	8063.8	D	1.0	2.2E-06	4.00E-06	0.56
300	1158.2	D	1.0	3.2E-07	5.00E-07	0.64
1000	145.5	D	1.0	4.0E-08	6.10E-08	0.66
3000	26.5	D	1.0	7.4E-09	1.10E-08	0.67
10,000	4.3	D	1.0	1.2E-09	2.10E-09	0.57
10	370776.5	E	1.0	1.0E-04	5.50E-04	0.19
30	85760.5	E	1.0	2.4E-05	9.90E-05	0.24
100	13870.3	E	1.0	3.9E-06	1.00E-05	0.39
300	2144.9	E	1.0	6.0E-07	1.20E-06	0.50
1000	288.5	E	1.0	8.0E-08	1.30E-07	0.62
3000	54.6	E	1.0	1.5E-08	2.40E-08	0.63
10,000	9.9	E	1.0	2.7E-09	5.60E-09	0.49

Table I.3 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	677719.4	F	1.0	1.9E-04	1.40E-03	0.13
30	150228.2	F	1.0	4.2E-05	2.20E-04	0.19
100	29517.8	F	1.0	8.2E-06	2.80E-05	0.29
300	4920.8	F	1.0	1.4E-06	3.40E-06	0.40
1000	670.7	F	1.0	1.9E-07	3.80E-07	0.49
3000	128.2	F	1.0	3.6E-08	6.70E-08	0.53
10,000	25.3	F	1.0	7.0E-09	1.60E-08	0.44
10	677719.4	G	1.0	1.9E-04	3.90E-03	0.05
30	150228.2	G	1.0	4.2E-05	4.60E-04	0.09
100	29517.8	G	1.0	8.2E-06	7.00E-05	0.12
300	4920.8	G	1.0	1.4E-06	9.30E-06	0.15
1000	670.7	G	1.0	1.9E-07	1.00E-06	0.19
3000	128.2	G	1.0	3.6E-08	1.90E-07	0.19
10,000	25.3	G	1.0	7.0E-09	4.40E-08	0.16
10	13590.2	A	3.4	3.8E-06	1.20E-05	0.31
30	2222.8	A	3.4	6.2E-07	1.30E-06	0.47
100	249.0	A	3.4	6.9E-08	1.20E-07	0.58
300	27.5	A	3.4	7.6E-09	1.30E-08	0.59
1000	1.0	A	3.4	2.7E-10	1.20E-09	0.23
3000	0.1	A	3.4	2.0E-11	1.50E-10	0.13
10,000	0.0	A	3.4	7.1E-12	1.70E-11	0.41
10	22010.5	B	3.4	6.1E-06	2.50E-05	0.24
30	3979.7	B	3.4	1.1E-06	3.00E-06	0.37
100	455.2	B	3.4	1.3E-07	2.70E-07	0.47
300	59.4	B	3.4	1.7E-08	3.10E-08	0.53
1000	5.6	B	3.4	1.5E-09	2.80E-09	0.55
3000	0.6	B	3.4	1.7E-10	3.40E-10	0.51
10,000	0.1	B	3.4	1.6E-11	3.80E-11	0.43
10	39414.7	C	3.4	1.1E-05	5.20E-05	0.21
30	8261.6	C	3.4	2.3E-06	6.50E-06	0.35
100	996.0	C	3.4	2.8E-07	6.00E-07	0.46
300	134.1	C	3.4	3.7E-08	6.90E-08	0.54
1000	14.8	C	3.4	4.1E-09	6.80E-09	0.61
3000	2.0	C	3.4	5.6E-10	9.50E-10	0.59
10,000	0.2	C	3.4	6.3E-11	1.40E-10	0.45
10	71210.2	D	3.4	2.0E-05	8.70E-05	0.23
30	16746.8	D	3.4	4.7E-06	1.20E-05	0.39

Table I.3 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
100	2372.6	D	3.4	6.6E-07	1.20E-06	0.55
300	340.7	D	3.4	9.5E-08	1.50E-07	0.63
1000	42.8	D	3.4	1.2E-08	1.80E-08	0.66
3000	7.8	D	3.4	2.2E-09	3.20E-09	0.68
10,000	1.3	D	3.4	3.5E-10	6.10E-10	0.58
10	107616.0	E	3.4	3.0E-05	1.60E-04	0.19
30	25280.8	E	3.4	7.0E-06	2.90E-05	0.24
100	4082.1	E	3.4	1.1E-06	3.00E-06	0.38
300	630.9	E	3.4	1.8E-07	3.50E-07	0.50
1000	84.8	E	3.4	2.4E-08	3.90E-08	0.60
3000	16.0	E	3.4	4.5E-09	7.00E-09	0.64
10,000	2.9	E	3.4	8.1E-10	1.60E-09	0.51
10	193682.6	F	3.4	5.4E-05	4.10E-04	0.13
30	44166.9	F	3.4	1.2E-05	6.60E-05	0.19
100	8693.1	F	3.4	2.4E-06	8.10E-06	0.30
300	1447.7	F	3.4	4.0E-07	9.90E-07	0.41
1000	197.3	F	3.4	5.5E-08	1.10E-07	0.50
3000	37.7	F	3.4	1.0E-08	2.00E-08	0.52
10,000	7.4	F	3.4	2.1E-09	4.60E-09	0.45
10	193682.6	G	3.4	5.4E-05	1.10E-03	0.05
30	44166.9	G	3.4	1.2E-05	1.30E-04	0.09
100	8693.1	G	3.4	2.4E-06	2.10E-05	0.11
300	1447.7	G	3.4	4.0E-07	2.70E-06	0.15
1000	197.3	G	3.4	5.5E-08	3.10E-07	0.18
3000	37.7	G	3.4	1.0E-08	5.50E-08	0.19
10,000	7.4	G	3.4	2.1E-09	1.30E-08	0.16
10	13401.3	C	10.0	3.7E-06	1.80E-05	0.21
30	2809.9	C	10.0	7.8E-07	2.20E-06	0.35
100	338.7	C	10.0	9.4E-08	2.00E-07	0.47
300	45.6	C	10.0	1.3E-08	2.30E-08	0.55
1000	5.0	C	10.0	1.4E-09	2.30E-09	0.61
3000	0.7	C	10.0	1.9E-10	3.20E-10	0.59
10,000	0.1	C	10.0	2.1E-11	4.90E-11	0.44
10	24160.2	D	10.0	6.7E-06	3.00E-05	0.22
30	5697.1	D	10.0	1.6E-06	4.10E-06	0.39
100	806.8	D	10.0	2.2E-07	4.00E-07	0.56
300	115.8	D	10.0	3.2E-08	5.00E-08	0.64

Table I.3 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
1000	14.5	D	10.0	4.0E-09	6.10E-09	0.66
3000	2.6	D	10.0	7.4E-10	1.10E-09	0.67
10,000	0.4	D	10.0	1.2E-10	2.10E-10	0.57
10	36452.9	E	10.0	1.0E-05	5.50E-05	0.18
30	8600.8	E	10.0	2.4E-06	9.90E-06	0.24
100	1388.2	E	10.0	3.9E-07	1.00E-06	0.39
300	214.5	E	10.0	6.0E-08	1.20E-07	0.50
1000	28.8	E	10.0	8.0E-09	1.30E-08	0.62
3000	5.5	E	10.0	1.5E-09	2.40E-09	0.63
10,000	1.0	E	10.0	2.7E-10	5.60E-10	0.49
10	6700.7	C	20.0	1.9E-06	8.80E-06	0.21
30	1405.0	C	20.0	3.9E-07	1.10E-06	0.35
100	169.3	C	20.0	4.7E-08	1.00E-07	0.47
300	22.8	C	20.0	6.3E-09	1.20E-08	0.53
1000	2.5	C	20.0	7.0E-10	1.20E-09	0.58
3000	0.3	C	20.0	9.5E-11	1.60E-10	0.59
10,000	0.0	C	20.0	1.1E-11	2.50E-11	0.43
10	12073.5	D	20.0	3.4E-06	1.50E-05	0.22
30	2849.0	D	20.0	7.9E-07	2.00E-06	0.40
100	403.4	D	20.0	1.1E-07	2.00E-07	0.56
300	57.9	D	20.0	1.6E-08	2.50E-08	0.64
1000	7.3	D	20.0	2.0E-09	3.10E-09	0.65
3000	1.3	D	20.0	3.7E-10	5.50E-10	0.67
10,000	0.2	D	20.0	6.0E-11	1.00E-10	0.60
10	18208.8	E	20.0	5.1E-06	2.80E-05	0.18
30	4301.1	E	20.0	1.2E-06	4.90E-06	0.24
100	694.1	E	20.0	1.9E-07	5.00E-07	0.39
300	107.3	E	20.0	3.0E-08	6.00E-08	0.50
1000	14.4	E	20.0	4.0E-09	6.70E-09	0.60
3000	2.7	E	20.0	7.6E-10	1.20E-09	0.63
10,000	0.5	E	20.0	1.4E-10	2.80E-10	0.49

Table I.4. AP Farm 6 m Stack with Extension @ 1359 m³/hr Ground Level Results Using ISC

Distance (m)	ISC 1-hr Average Conc. (µg/m ³)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	0.01914	A	1.0	7.23E-09	1.30E-03	0.00
30	91.5787	A	1.0	3.46E-05	3.70E-03	0.01
100	458.494	A	1.0	1.73E-04	5.20E-04	0.33
300	88.4362	A	1.0	3.34E-05	6.10E-05	0.55
1000	3.35817	A	1.0	1.27E-06	5.70E-06	0.22
3000	0.24339	A	1.0	9.19E-08	6.90E-07	0.13
10,000	0.08628	A	1.0	3.26E-08	7.70E-08	0.42
10	0.00364	B	1.0	1.37E-09	1.10E-05	0.00
30	26.9842	B	1.0	1.02E-05	3.70E-03	0.00
100	551.681	B	1.0	2.08E-04	1.10E-03	0.19
300	176.439	B	1.0	6.66E-05	1.40E-04	0.48
1000	18.6981	B	1.0	7.06E-06	1.30E-05	0.54
3000	2.13016	B	1.0	8.04E-07	1.60E-06	0.50
10,000	0.19837	B	1.0	7.49E-08	1.80E-07	0.42
10	0.00074	C	1.0	2.79E-10	4.90E-10	0.57
30	4.02608	C	1.0	1.52E-06	2.00E-03	0.00
100	476.304	C	1.0	1.80E-04	2.10E-03	0.09
300	339.114	C	1.0	1.28E-04	3.10E-04	0.41
1000	48.8277	C	1.0	1.84E-05	3.10E-05	0.59
3000	6.8008	C	1.0	2.57E-06	4.40E-06	0.58
10,000	0.77227	C	1.0	2.92E-07	6.70E-07	0.44
10	0.00023	D	1.0	8.68E-11	1.50E-16	
30	0.38691	D	1.0	1.46E-07	5.30E-04	0.00
100	123.065	D	1.0	4.65E-05	3.10E-03	0.01
300	517.566	D	1.0	1.95E-04	6.30E-04	0.31
1000	129.083	D	1.0	4.87E-05	8.20E-05	0.59
3000	25.7104	D	1.0	9.71E-06	1.50E-05	0.65
10,000	4.31156	D	1.0	1.63E-06	2.80E-06	0.58
10	0.00143	E	1.0	5.40E-10	0.00E+00	
30	0.07004	E	1.0	2.64E-08	1.30E-08	2.03
100	98.5977	E	1.0	3.72E-05	2.00E-03	0.02
300	744.134	E	1.0	2.81E-04	1.30E-03	0.22
1000	240.969	E	1.0	9.10E-05	1.80E-04	0.51
3000	52.0261	E	1.0	1.96E-05	3.20E-05	0.61
10,000	9.75851	E	1.0	3.68E-06	7.50E-06	0.49
10	0.00025	F	1.0	9.44E-11	0.00E+00	
30	0.00402	F	1.0	1.52E-09	3.50E-25	1.00

Table I.4 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
100	8.12817	F	1.0	3.07E-06	1.20E-04	0.03
300	572.543	F	1.0	2.16E-04	1.90E-03	0.11
1000	455.578	F	1.0	1.72E-04	4.50E-04	0.38
3000	115.463	F	1.0	4.36E-05	8.80E-05	0.50
10,000	24.4382	F	1.0	9.23E-06	2.10E-05	0.44
10	0.49552	A	3.4	1.87E-07	3.80E-04	0.00
30	370.746	A	3.4	1.40E-04	1.10E-03	0.13
100	204.33	A	3.4	7.71E-05	1.50E-04	0.51
300	27.02	A	3.4	1.02E-05	1.80E-05	0.57
1000	0.98818	A	3.4	3.73E-07	1.70E-06	0.22
3000	0.07159	A	3.4	2.70E-08	2.00E-07	0.14
10,000	0.02538	A	3.4	9.58E-09	2.30E-08	0.42
10	0.01115	B	3.4	4.21E-09	3.40E-06	0.00
30	227.493	B	3.4	8.59E-05	1.10E-03	0.08
100	323.991	B	3.4	1.22E-04	3.30E-04	0.37
300	56.9644	B	3.4	2.15E-05	4.10E-05	0.52
1000	5.53928	B	3.4	2.09E-06	3.90E-06	0.54
3000	0.62693	B	3.4	2.37E-07	4.70E-07	0.50
10,000	0.05835	B	3.4	2.20E-08	5.20E-08	0.42
10	0.00002	C	3.4	7.55E-12	1.60E-10	0.05
30	52.1526	C	3.4	1.97E-05	5.80E-04	0.03
100	504.245	C	3.4	1.90E-04	6.10E-04	0.31
300	122.091	C	3.4	4.61E-05	9.00E-05	0.51
1000	14.6936	C	3.4	5.55E-06	9.20E-06	0.60
3000	2.0064	C	3.4	7.57E-07	1.30E-06	0.58
10,000	0.22721	C	3.4	8.58E-08	2.00E-07	0.43
10	0	D	3.4	0.00E+00	5.30E-17	0.00
30	0.94016	D	3.4	3.55E-07	1.60E-04	0.00
100	448.143	D	3.4	1.69E-04	9.00E-04	0.19
300	262.044	D	3.4	9.89E-05	1.80E-04	0.55
1000	41.2102	D	3.4	1.56E-05	2.40E-05	0.65
3000	7.7147	D	3.4	2.91E-06	4.40E-06	0.66
10,000	1.27403	D	3.4	4.81E-07	8.30E-07	0.58
10	0	E	3.4	0.00E+00	0.00E+00	
30	0.02698	E	3.4	1.02E-08	3.90E-09	2.61
100	261.669	E	3.4	9.88E-05	5.90E-04	0.17
300	381.956	E	3.4	1.44E-04	3.70E-04	0.39

Table I.4 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
1000	78.1185	E	3.4	2.95E-05	5.20E-05	0.57
3000	15.7012	E	3.4	5.93E-06	9.40E-06	0.63
10,000	2.89133	E	3.4	1.09E-06	2.20E-06	0.50
10	0	F	3.4	0.00E+00	0.00E+00	
30	0.00001	F	3.4	3.78E-12	1.20E-25	
100	31.9582	F	3.4	1.21E-05	3.40E-05	0.35
300	451.527	F	3.4	1.70E-04	5.50E-04	0.31
1000	161.922	F	3.4	6.11E-05	1.30E-04	0.47
3000	35.765	F	3.4	1.35E-05	2.60E-05	0.52
10,000	7.31529	F	3.4	2.76E-06	6.20E-06	0.45
10	0	G	3.4	0.00E+00	0.00E+00	
30	0.00001	G	3.4	3.78E-12	0.00E+00	
100	31.9582	G	3.4	1.21E-05	2.10E-10	0.00
300	451.527	G	3.4	1.70E-04	2.20E-04	0.77
1000	161.922	G	3.4	6.11E-05	2.80E-04	0.22
3000	35.765	G	3.4	1.35E-05	6.70E-05	0.20
10,000	7.31529	G	3.4	2.76E-06	1.70E-05	0.16
10	0.00003	C	10.0	1.13E-11	5.40E-11	0.21
30	99.4016	C	10.0	3.75E-05	2.00E-04	0.19
100	221.607	C	10.0	8.37E-05	2.10E-04	0.40
300	43.0225	C	10.0	1.62E-05	3.10E-05	0.52
1000	5.01572	C	10.0	1.89E-06	3.10E-06	0.61
3000	0.68254	C	10.0	2.58E-07	4.40E-07	0.59
10,000	0.07726	C	10.0	2.92E-08	6.70E-08	0.44
10	0	D	10.0	0.00E+00	1.90E-17	0.00
30	5.60871	D	10.0	2.12E-06	5.40E-05	0.04
100	281.395	D	10.0	1.06E-04	3.10E-04	0.34
300	98.4477	D	10.0	3.72E-05	6.30E-05	0.59
1000	14.2142	D	10.0	5.37E-06	8.20E-06	0.65
3000	2.63217	D	10.0	9.94E-07	1.50E-06	0.66
10,000	0.43352	D	10.0	1.64E-07	2.80E-07	0.58
10	0	E	10.0	0.00E+00	0.00E+00	
30	0.22893	E	10.0	8.64E-08	1.40E-09	62
100	238.437	E	10.0	9.00E-05	2.00E-04	0.45
300	157.012	E	10.0	5.93E-05	1.30E-04	0.46
1000	27.4107	E	10.0	1.03E-05	1.80E-05	0.57
3000	5.38283	E	10.0	2.03E-06	3.20E-06	0.64

Table I.4 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10,000	0.98538	E	10.0	3.72E-07	7.50E-07	0.50
10	0.00025	C	20.0	9.44E-11	5.90E-07	0.0002
30	87.3134	C	20.0	3.30E-05	1.90E-04	0.17
100	119.141	C	20.0	4.50E-05	5.50E-05	0.82
300	21.7259	C	20.0	8.20E-06	7.00E-06	1.17
1000	2.51062	C	20.0	9.48E-07	6.60E-07	1.44
3000	0.34132	C	20.0	1.29E-07	7.90E-08	1.63
10,000	0.03863	C	20.0	1.46E-08	8.90E-09	1.64
10	0	D	20.0	0.00E+00	9.50E-18	
30	9.08378	D	20.0	3.43E-06	2.70E-05	0.13
100	168.274	D	20.0	6.35E-05	1.50E-04	0.42
300	50.6153	D	20.0	1.91E-05	3.10E-05	0.62
1000	7.13551	D	20.0	2.69E-06	4.10E-06	0.66
3000	1.31736	D	20.0	4.97E-07	7.40E-07	0.67
10,000	0.21681	D	20.0	8.18E-08	1.40E-07	0.58
10	0	E	20.0	0.00E+00	0.00E+00	
30	0.65685	E	20.0	2.48E-07	6.80E-10	365
100	160.561	E	20.0	6.06E-05	1.00E-04	0.61
300	82.814	E	20.0	3.13E-05	6.30E-05	0.50
1000	13.826	E	20.0	5.22E-06	8.80E-06	0.59
3000	2.69762	E	20.0	1.02E-06	1.60E-06	0.64
10,000	0.49301	E	20.0	1.86E-07	3.80E-07	0.49

Table I.5. AP Farm 6 m Stack with Extension @ 1359 m³/hr Plume Centerline Results Using ISC

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	42.55277	A	1.0	1.61E-05	2.70E-02	0.00
30	620.462	A	1.0	2.34E-04	3.40E-03	0.07
100	464.38	A	1.0	1.75E-04	5.00E-04	0.35
300	87.82569	A	1.0	3.32E-05	6.10E-05	0.54
1000	3.35789	A	1.0	1.27E-06	5.70E-06	0.22
3000	0.24339	A	1.0	9.19E-08	6.90E-07	0.13
10,000	0.08628	A	1.0	3.26E-08	7.70E-08	0.42
10	24.6503	B	1.0	9.31E-06	5.90E-02	0.00
30	504.1921	B	1.0	1.90E-04	6.90E-03	0.03
100	622.2084	B	1.0	2.35E-04	1.00E-03	0.23
300	173.9664	B	1.0	6.57E-05	1.40E-04	0.47
1000	18.67126	B	1.0	7.05E-06	1.30E-05	0.54
3000	2.12988	B	1.0	8.04E-07	1.60E-06	0.50
10,000	0.19837	B	1.0	7.49E-08	1.80E-07	0.42
10	14.31335	C	1.0	5.40E-06	1.20E-01	0.00
30	313.3193	C	1.0	1.18E-04	1.50E-02	0.01
100	808.716	C	1.0	3.05E-04	1.80E-03	0.17
300	333.0389	C	1.0	1.26E-04	3.00E-04	0.42
1000	48.61464	C	1.0	1.84E-05	3.10E-05	0.59
3000	6.79657	C	1.0	2.57E-06	4.40E-06	0.58
10,000	0.77221	C	1.0	2.92E-07	6.70E-07	0.44
10	9.28305	D	1.0	3.50E-06	2.00E-01	0.00
30	147.3701	D	1.0	5.56E-05	2.80E-02	0.00
100	725.7459	D	1.0	2.74E-04	3.00E-03	0.09
300	546.178	D	1.0	2.06E-04	5.90E-04	0.35
1000	127.4189	D	1.0	4.81E-05	8.10E-05	0.59
3000	25.61066	D	1.0	9.67E-06	1.50E-05	0.64
10,000	4.30747	D	1.0	1.63E-06	2.80E-06	0.58
10	121.2127	E	1.0	4.58E-05	4.00E-01	0.00
30	333.6909	E	1.0	1.26E-04	7.00E-02	0.00
100	1438.042	E	1.0	5.43E-04	6.90E-03	0.08
300	890.4918	E	1.0	3.36E-04	1.10E-03	0.31
1000	235.2297	E	1.0	8.88E-05	1.70E-04	0.52
3000	51.56588	E	1.0	1.95E-05	3.20E-05	0.61
10,000	9.73197	E	1.0	3.67E-06	7.50E-06	0.49
10	129.7242	F	1.0	4.90E-05	6.50E-01	0.00
30	252.8526	F	1.0	9.55E-05	1.70E-01	0.00
100	1245.874	F	1.0	4.70E-04	1.90E-02	0.02
300	1368.1	F	1.0	5.16E-04	2.40E-03	0.22

Table I.5 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
1000	445.3565	F	1.0	1.68E-04	4.20E-04	0.40
3000	113.2878	F	1.0	4.28E-05	8.60E-05	0.50
10,000	24.25431	F	1.0	9.16E-06	2.10E-05	0.44
10	2218.001	A	3.4	8.37E-04	8.00E-03	0.10
30	941.9138	A	3.4	3.56E-04	1.00E-03	0.36
100	193.4719	A	3.4	7.30E-05	1.50E-04	0.49
300	26.81788	A	3.4	1.01E-05	1.80E-05	0.56
1000	0.9881	A	3.4	3.73E-07	1.70E-06	0.22
3000	0.07159	A	3.4	2.70E-08	2.00E-07	0.14
10,000	0.02538	A	3.4	9.58E-09	2.30E-08	0.42
10	2146.335	B	3.4	8.10E-04	1.80E-02	0.05
30	1499.934	B	3.4	5.66E-04	2.10E-03	0.27
100	307.345	B	3.4	1.16E-04	3.00E-04	0.39
300	55.96998	B	3.4	2.11E-05	4.00E-05	0.53
1000	5.53122	B	3.4	2.09E-06	3.90E-06	0.54
3000	0.62685	B	3.4	2.37E-07	4.70E-07	0.50
10,000	0.05835	B	3.4	2.20E-08	5.20E-08	0.42
10	1604.031	C	3.4	6.06E-04	3.90E-02	0.02
30	2433.707	C	3.4	9.19E-04	4.50E-03	0.20
100	538.2776	C	3.4	2.03E-04	5.40E-04	0.38
300	117.9605	C	3.4	4.45E-05	8.80E-05	0.51
1000	14.62638	C	3.4	5.52E-06	9.20E-06	0.60
3000	2.00514	C	3.4	7.57E-07	1.30E-06	0.58
10,000	0.2272	C	3.4	8.58E-08	2.00E-07	0.43
10	843.2117	D	3.4	3.18E-04	6.90E-02	0.00
30	2833.37	D	3.4	1.07E-03	8.30E-03	0.13
100	1019.68	D	3.4	3.85E-04	8.70E-04	0.44
300	247.3253	D	3.4	9.34E-05	1.70E-04	0.55
1000	40.56792	D	3.4	1.53E-05	2.40E-05	0.64
3000	7.68351	D	3.4	2.90E-06	4.30E-06	0.67
10,000	1.27281	D	3.4	4.80E-07	8.30E-07	0.58
10	610.9882	E	3.4	2.31E-04	1.60E-01	0.00
30	2642.134	E	3.4	9.97E-04	2.20E-02	0.05
100	1555.92	E	3.4	5.87E-04	2.00E-03	0.29
300	376.6641	E	3.4	1.42E-04	3.30E-04	0.43
1000	75.71793	E	3.4	2.86E-05	5.00E-05	0.57
3000	15.55443	E	3.4	5.87E-06	9.30E-06	0.63
10,000	2.88335	E	3.4	1.09E-06	2.20E-06	0.49

Table I.5 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	349.2771	F	3.4	1.32E-04	3.60E-01	0.00
30	1569.645	F	3.4	5.93E-04	5.80E-02	0.01
100	2411.503	F	3.4	9.10E-04	5.70E-03	0.16
300	673.2727	F	3.4	2.54E-04	7.00E-04	0.36
1000	153.32	F	3.4	5.79E-05	1.20E-04	0.48
3000	35.00491	F	3.4	1.32E-05	2.50E-05	0.53
10,000	7.25816	F	3.4	2.74E-06	6.10E-06	0.45
10	349.2771	G	3.4	1.32E-04	6.10E-01	0.00
30	1569.645	G	3.4	5.93E-04	1.50E-01	0.00
100	2411.503	G	3.4	9.10E-04	1.60E-02	0.06
300	673.2727	G	3.4	2.54E-04	1.90E-03	0.13
1000	153.32	G	3.4	5.79E-05	2.50E-04	0.23
3000	35.00491	G	3.4	1.32E-05	6.20E-05	0.21
10,000	7.25816	G	3.4	2.74E-06	1.60E-05	0.17
10	6823.229	C	10.0	2.58E-03	1.30E-02	0.20
30	1453.483	C	10.0	5.49E-04	1.50E-03	0.37
100	207.8726	C	10.0	7.85E-05	1.80E-04	0.44
300	41.44296	C	10.0	1.56E-05	3.00E-05	0.52
1000	4.99259	C	10.0	1.88E-06	3.10E-06	0.61
3000	0.68211	C	10.0	2.57E-07	4.40E-07	0.59
10,000	0.07725	C	10.0	2.92E-08	6.70E-08	0.44
10	8910.264	D	10.0	3.36E-03	2.50E-02	0.13
30	3029.992	D	10.0	1.14E-03	2.80E-03	0.41
100	416.5238	D	10.0	1.57E-04	3.00E-04	0.52
300	90.8175	D	10.0	3.43E-05	5.90E-05	0.58
1000	13.98591	D	10.0	5.28E-06	8.10E-06	0.65
3000	2.62145	D	10.0	9.90E-07	1.50E-06	0.66
10,000	0.43311	D	10.0	1.63E-07	2.80E-07	0.58
10	9459.194	E	10.0	3.57E-03	6.30E-02	0.06
30	4617.982	E	10.0	1.74E-03	7.40E-03	0.24
100	707.71	E	10.0	2.67E-04	6.90E-04	0.39
300	143.3794	E	10.0	5.41E-05	1.10E-04	0.49
1000	26.50633	E	10.0	1.00E-05	1.70E-05	0.59
3000	5.33167	E	10.0	2.01E-06	3.20E-06	0.63
10,000	0.98265	E	10.0	3.71E-07	7.50E-07	0.49
10	5518.907	C	20.0	2.08E-03	6.80E-03	0.31
30	779.1539	C	20.0	2.94E-04	7.60E-04	0.39
100	107.426	C	20.0	4.06E-05	9.20E-05	0.44
300	20.91072	C	20.0	7.89E-06	1.50E-05	0.53

Table I.5 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
1000	2.49902	C	20.0	9.43E-07	1.60E-06	0.59
3000	0.34111	C	20.0	1.29E-07	2.20E-07	0.59
10,000	0.03863	C	20.0	1.46E-08	3.30E-08	0.44
10	11154.45	D	20.0	4.21E-03	1.20E-02	0.35
30	1773.375	D	20.0	6.69E-04	1.40E-03	0.48
100	214.1807	D	20.0	8.09E-05	1.50E-04	0.54
300	46.38871	D	20.0	1.75E-05	2.90E-05	0.60
1000	7.01994	D	20.0	2.65E-06	4.10E-06	0.65
3000	1.31199	D	20.0	4.95E-07	7.40E-07	0.67
10,000	0.2166	D	20.0	8.18E-08	1.40E-07	0.58
10	16839.41	E	20.0	6.36E-03	3.20E-02	0.20
30	2959.926	E	20.0	1.12E-03	3.70E-03	0.30
100	366.5523	E	20.0	1.38E-04	3.50E-04	0.40
300	73.9211	E	20.0	2.79E-05	5.50E-05	0.51
1000	13.36108	E	20.0	5.04E-06	8.50E-06	0.59
3000	2.67186	E	20.0	1.01E-06	1.60E-06	0.63
10,000	0.49164	E	20.0	1.86E-07	3.80E-07	0.49

Table I.6. AY Farm 16.7 m Vent @ 1699 m³/hr Ground Level Results Using ISC

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	215.5304	A	1.0	1.02E-04	3.30E-02	0.00
30	1319.034	A	1.0	6.23E-04	3.80E-03	0.16
100	380.2688	A	1.0	1.79E-04	4.30E-04	0.42
300	78.82172	A	1.0	3.72E-05	7.10E-05	0.52
1000	3.35353	A	1.0	1.58E-06	7.10E-06	0.22
3000	0.24339	A	1.0	1.15E-07	8.60E-07	0.13
10,000	0.08628	A	1.0	4.07E-08	9.70E-08	0.42
10	113.1091	B	1.0	5.34E-05	7.30E-02	0.00
30	1359.672	B	1.0	6.42E-04	8.60E-03	0.07
100	624.4468	B	1.0	2.95E-04	8.00E-04	0.37
300	139.8648	B	1.0	6.60E-05	1.50E-04	0.44
1000	18.25471	B	1.0	8.62E-06	1.60E-05	0.54
3000	2.12549	B	1.0	1.00E-06	2.00E-06	0.50
10,000	0.19834	B	1.0	9.36E-08	2.20E-07	0.43
10	53.00046	C	1.0	2.50E-05	1.50E-01	0.00
30	1066.118	C	1.0	5.03E-04	1.90E-02	0.03
100	1105.935	C	1.0	5.22E-04	1.70E-03	0.31
300	247.1649	C	1.0	1.17E-04	2.70E-04	0.43
1000	45.39227	C	1.0	2.14E-05	3.70E-05	0.58
3000	6.7303	C	1.0	3.18E-06	5.40E-06	0.59
10,000	0.77137	C	1.0	3.64E-07	8.40E-07	0.43
10	26.54652	D	1.0	1.25E-05	2.40E-01	0.00
30	513.9869	D	1.0	2.43E-04	3.40E-02	0.01
100	1496.783	D	1.0	7.06E-04	3.40E-03	0.21
300	492.7026	D	1.0	2.33E-04	4.60E-04	0.51
1000	104.2115	D	1.0	4.92E-05	8.70E-05	0.57
3000	24.09261	D	1.0	1.14E-05	1.80E-05	0.63
10,000	4.24345	D	1.0	2.00E-06	3.50E-06	0.57
1	0	E	1.0	0.00E+00	9.90E-01	0.00
3	0.64321	E	1.0	3.04E-07	9.00E-01	0.00
10	217.579	E	1.0	1.03E-04	4.60E-01	0.00
30	777.991	E	1.0	3.67E-04	8.60E-02	0.00
100	2344.652	E	1.0	1.11E-03	8.60E-03	0.13
300	872.6281	E	1.0	4.12E-04	1.00E-03	0.41
1000	168.1547	E	1.0	7.94E-05	1.50E-04	0.53
3000	44.87262	E	1.0	2.12E-05	3.60E-05	0.59
10,000	9.31441	E	1.0	4.40E-06	9.00E-06	0.49

Table I.6 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
1	0.00012	F	1.0	5.66E-11	1.00E+00	0.00
10	220.4963	F	1.0	1.04E-04	7.00E-01	0.00
30	546.3916	F	1.0	2.58E-04	2.10E-01	0.00
100	2473.516	F	1.0	1.17E-03	2.40E-02	0.05
300	1661.621	F	1.0	7.84E-04	2.90E-03	0.27
1000	321.504	F	1.0	1.52E-04	3.30E-04	0.46
3000	86.26858	F	1.0	4.07E-05	8.00E-05	0.51
10,000	21.56917	F	1.0	1.02E-05	2.30E-05	0.44
10	3999.742	A	3.4	1.89E-03	9.90E-03	0.19
30	1033.407	A	3.4	4.88E-04	1.10E-03	0.44
100	128.5632	A	3.4	6.07E-05	1.30E-04	0.47
300	24.14202	A	3.4	1.14E-05	2.10E-05	0.54
1000	0.98687	A	3.4	4.66E-07	2.10E-06	0.22
3000	0.07159	A	3.4	3.38E-08	2.50E-07	0.14
10,000	0.02538	A	3.4	1.20E-08	2.80E-08	0.43
10	4779.425	B	3.4	2.26E-03	2.30E-02	0.10
30	1762.138	B	3.4	8.32E-04	2.60E-03	0.32
100	225.5119	B	3.4	1.06E-04	2.40E-04	0.44
300	44.59636	B	3.4	2.10E-05	4.30E-05	0.49
1000	5.41503	B	3.4	2.56E-06	4.70E-06	0.54
3000	0.62564	B	3.4	2.95E-07	5.80E-07	0.51
10,000	0.05834	B	3.4	2.75E-08	6.50E-08	0.42
10	4577.031	C	3.4	2.16E-03	4.80E-02	0.05
30	3270.295	C	3.4	1.54E-03	5.60E-03	0.28
100	484.8199	C	3.4	2.29E-04	5.10E-04	0.45
300	81.53083	C	3.4	3.85E-05	7.90E-05	0.49
1000	13.69879	C	3.4	6.47E-06	1.10E-05	0.59
3000	1.98683	C	3.4	9.38E-07	1.60E-06	0.59
10,000	0.22697	C	3.4	1.07E-07	2.50E-07	0.43
10	2608.071	D	3.4	1.23E-03	8.50E-02	0.01
30	5032.377	D	3.4	2.38E-03	1.00E-02	0.24
100	1108.366	D	3.4	5.23E-04	9.90E-04	0.53
300	170.9839	D	3.4	8.07E-05	1.40E-04	0.58
1000	33.01256	D	3.4	1.56E-05	2.60E-05	0.60
3000	7.24963	D	3.4	3.42E-06	5.20E-06	0.66
10,000	1.25509	D	3.4	5.92E-07	1.00E-06	0.59

Table I.6 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	1757.195	E	3.4	8.29E-04	2.00E-01	0.00
30	5797.483	E	3.4	2.74E-03	2.70E-02	0.10
100	1816.239	E	3.4	8.57E-04	2.50E-03	0.34
300	309.4468	E	3.4	1.46E-04	3.00E-04	0.49
1000	53.4187	E	3.4	2.52E-05	4.50E-05	0.56
3000	13.66274	E	3.4	6.45E-06	1.10E-05	0.59
10,000	2.7703	E	3.4	1.31E-06	2.60E-06	0.50
10	718.9473	F	3.4	3.39E-04	4.10E-01	0.00
30	4859.543	F	3.4	2.29E-03	7.20E-02	0.03
100	3345.784	F	3.4	1.58E-03	7.10E-03	0.22
300	691.0891	F	3.4	3.26E-04	8.50E-04	0.38
1000	101.8673	F	3.4	4.81E-05	9.60E-05	0.50
3000	26.79799	F	3.4	1.26E-05	2.40E-05	0.53
10,000	6.50509	F	3.4	3.07E-06	6.70E-06	0.46
10	718.9473	G	3.4	3.39E-04	6.60E-01	0.00
30	4859.543	G	3.4	2.29E-03	1.80E-01	0.01
100	3345.784	G	3.4	1.58E-03	2.00E-02	0.08
300	691.0891	G	3.4	3.26E-04	2.40E-03	0.14
1000	101.8673	G	3.4	4.81E-05	2.60E-04	0.18
3000	26.79799	G	3.4	1.26E-05	4.80E-05	0.26
10,000	6.50509	G	3.4	3.07E-06	1.40E-05	0.22
10	10928.13	C	10.0	5.16E-03	1.70E-02	0.30
30	1553.933	C	10.0	7.33E-04	1.90E-03	0.39
100	171.3441	C	10.0	8.09E-05	1.70E-04	0.48
300	28.58356	C	10.0	1.35E-05	2.70E-05	0.50
1000	4.69221	C	10.0	2.21E-06	3.70E-06	0.60
3000	0.67624	C	10.0	3.19E-07	5.40E-07	0.59
10,000	0.07718	C	10.0	3.64E-08	8.40E-08	0.43
10	21878.76	D	10.0	1.03E-02	3.10E-02	0.33
30	3524.326	D	10.0	1.66E-03	3.50E-03	0.48
100	415.6107	D	10.0	1.96E-04	3.40E-04	0.58
300	59.35934	D	10.0	2.80E-05	4.60E-05	0.61
1000	11.46665	D	10.0	5.41E-06	8.70E-06	0.62
3000	2.48115	D	10.0	1.17E-06	1.80E-06	0.65
10,000	0.42742	D	10.0	2.02E-07	3.50E-07	0.58

Table I.6 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	32753.36	E	10.0	1.55E-02	7.70E-02	0.20
30	5859.729	E	10.0	2.77E-03	9.30E-03	0.30
100	730.4321	E	10.0	3.45E-04	8.60E-04	0.40
300	108.2494	E	10.0	5.11E-05	1.00E-04	0.51
1000	18.72065	E	10.0	8.84E-06	1.50E-05	0.59
3000	4.71154	E	10.0	2.22E-06	3.60E-06	0.62
10,000	0.94621	E	10.0	4.47E-07	9.00E-07	0.50
10	5790.15	C	20.0	2.73E-03	8.50E-03	0.32
30	783.8774	C	20.0	3.70E-04	9.50E-04	0.39
100	85.75744	C	20.0	4.05E-05	8.70E-05	0.47
300	14.42887	C	20.0	6.81E-06	1.30E-05	0.52
1000	2.35166	C	20.0	1.11E-06	1.90E-06	0.58
3000	0.33823	C	20.0	1.60E-07	2.70E-07	0.59
10,000	0.03859	C	20.0	1.82E-08	4.20E-08	0.43
10	12297.22	D	20.0	5.80E-03	1.60E-02	0.36
30	1798.08	D	20.0	8.49E-04	1.80E-03	0.47
100	208.3232	D	20.0	9.83E-05	1.70E-04	0.58
300	29.77239	D	20.0	1.41E-05	2.30E-05	0.61
1000	5.77259	D	20.0	2.72E-06	4.40E-06	0.62
3000	1.24319	D	20.0	5.87E-07	8.90E-07	0.66
10,000	0.21382	D	20.0	1.01E-07	1.70E-07	0.59
10	19429.86	E	20.0	9.17E-03	4.00E-02	0.23
30	3026.161	E	20.0	1.43E-03	4.70E-03	0.30
100	366.7962	E	20.0	1.73E-04	4.30E-04	0.40
300	54.17096	E	20.0	2.56E-05	5.10E-05	0.50
1000	9.44989	E	20.0	4.46E-06	7.70E-06	0.58
3000	2.36646	E	20.0	1.12E-06	1.80E-06	0.62
10,000	0.4738	E	20.0	2.24E-07	4.50E-07	0.50

Table I.7. AY Farm 16.7 m Vent @ 1699 m³/hr Plume Center Line Results Using ISC

Distance (m)	ISC 1-hr Average Conc. (µg/m ³)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	215.5304	A	1.0	1.02E-04	3.30E-02	0.00
30	1319.034	A	1.0	6.23E-04	3.80E-03	0.16
100	380.2688	A	1.0	1.79E-04	4.30E-04	0.42
300	78.82172	A	1.0	3.72E-05	7.10E-05	0.52
1000	3.35353	A	1.0	1.58E-06	7.10E-06	0.22
3000	0.24339	A	1.0	1.15E-07	8.60E-07	0.13
10,000	0.08628	A	1.0	4.07E-08	9.70E-08	0.42
10	113.1091	B	1.0	5.34E-05	7.30E-02	0.00
30	1359.672	B	1.0	6.42E-04	8.60E-03	0.07
100	624.4468	B	1.0	2.95E-04	8.00E-04	0.37
300	139.8648	B	1.0	6.60E-05	1.50E-04	0.44
1000	18.25471	B	1.0	8.62E-06	1.60E-05	0.54
3000	2.12549	B	1.0	1.00E-06	2.00E-06	0.50
10,000	0.19834	B	1.0	9.36E-08	2.20E-07	0.43
10	53.00046	C	1.0	2.50E-05	1.50E-01	0.00
30	1066.118	C	1.0	5.03E-04	1.90E-02	0.03
100	1105.935	C	1.0	5.22E-04	1.70E-03	0.31
300	247.1649	C	1.0	1.17E-04	2.70E-04	0.43
1000	45.39227	C	1.0	2.14E-05	3.70E-05	0.58
3000	6.7303	C	1.0	3.18E-06	5.40E-06	0.59
10,000	0.77137	C	1.0	3.64E-07	8.40E-07	0.43
10	26.54652	D	1.0	1.25E-05	2.40E-01	0.00
30	513.9869	D	1.0	2.43E-04	3.40E-02	0.01
100	1496.783	D	1.0	7.06E-04	3.40E-03	0.21
300	492.7026	D	1.0	2.33E-04	4.60E-04	0.51
1000	104.2115	D	1.0	4.92E-05	8.70E-05	0.57
3000	24.09261	D	1.0	1.14E-05	1.80E-05	0.63
10,000	4.24345	D	1.0	2.00E-06	3.50E-06	0.57
10	217.579	E	1.0	1.03E-04	4.60E-01	0.00
30	777.991	E	1.0	3.67E-04	8.60E-02	0.00
100	2344.652	E	1.0	1.11E-03	8.60E-03	0.13
300	872.6281	E	1.0	4.12E-04	1.00E-03	0.41
1000	168.1547	E	1.0	7.94E-05	1.50E-04	0.53
3000	44.87262	E	1.0	2.12E-05	3.60E-05	0.59
10,000	9.31441	E	1.0	4.40E-06	9.00E-06	0.49

Table I.7 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	220.4963	F	1.0	1.04E-04	7.00E-01	0.00
30	546.3916	F	1.0	2.58E-04	2.10E-01	0.00
100	2473.516	F	1.0	1.17E-03	2.40E-02	0.05
300	1661.621	F	1.0	7.84E-04	2.90E-03	0.27
1000	321.504	F	1.0	1.52E-04	3.30E-04	0.46
3000	86.26858	F	1.0	4.07E-05	8.00E-05	0.51
10,000	21.56917	F	1.0	1.02E-05	2.30E-05	0.44
10	3999.742	A	3.4	1.89E-03	9.90E-03	0.19
30	1033.407	A	3.4	4.88E-04	1.10E-03	0.44
100	128.5632	A	3.4	6.07E-05	1.30E-04	0.47
300	24.14202	A	3.4	1.14E-05	2.10E-05	0.54
1000	0.98687	A	3.4	4.66E-07	2.10E-06	0.22
3000	0.07159	A	3.4	3.38E-08	2.50E-07	0.14
10,000	0.02538	A	3.4	1.20E-08	2.80E-08	0.43
10	4779.425	B	3.4	2.26E-03	2.30E-02	0.10
30	1762.138	B	3.4	8.32E-04	2.60E-03	0.32
100	225.5119	B	3.4	1.06E-04	2.40E-04	0.44
300	44.59636	B	3.4	2.10E-05	4.30E-05	0.49
1000	5.41503	B	3.4	2.56E-06	4.70E-06	0.54
3000	0.62564	B	3.4	2.95E-07	5.80E-07	0.51
10,000	0.05834	B	3.4	2.75E-08	6.50E-08	0.42
10	4577.031	C	3.4	2.16E-03	4.80E-02	0.05
30	3270.295	C	3.4	1.54E-03	5.60E-03	0.28
100	484.8199	C	3.4	2.29E-04	5.10E-04	0.45
300	81.53083	C	3.4	3.85E-05	7.90E-05	0.49
1000	13.69879	C	3.4	6.47E-06	1.10E-05	0.59
3000	1.98683	C	3.4	9.38E-07	1.60E-06	0.59
10,000	0.22697	C	3.4	1.07E-07	2.50E-07	0.43
10	2608.071	D	3.4	1.23E-03	8.50E-02	0.01
30	5032.377	D	3.4	2.38E-03	1.00E-02	0.24
100	1108.366	D	3.4	5.23E-04	9.90E-04	0.53
300	170.9839	D	3.4	8.07E-05	1.40E-04	0.58
1000	33.01256	D	3.4	1.56E-05	2.60E-05	0.60
3000	7.24963	D	3.4	3.42E-06	5.20E-06	0.66
10,000	1.25509	D	3.4	5.92E-07	1.00E-06	0.59

Table I.7 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	1757.195	E	3.4	8.29E-04	2.00E-01	0.00
30	5797.483	E	3.4	2.74E-03	2.70E-02	0.10
100	1816.239	E	3.4	8.57E-04	2.50E-03	0.34
300	309.4468	E	3.4	1.46E-04	3.00E-04	0.49
1000	53.4187	E	3.4	2.52E-05	4.50E-05	0.56
3000	13.66274	E	3.4	6.45E-06	1.10E-05	0.59
10,000	2.7703	E	3.4	1.31E-06	2.60E-06	0.50
10	718.9473	F	3.4	3.39E-04	4.10E-01	0.00
30	4859.543	F	3.4	2.29E-03	7.20E-02	0.03
100	3345.784	F	3.4	1.58E-03	7.10E-03	0.22
300	691.0891	F	3.4	3.26E-04	8.50E-04	0.38
1000	101.8673	F	3.4	4.81E-05	9.60E-05	0.50
3000	26.79799	F	3.4	1.26E-05	2.40E-05	0.53
10,000	6.50509	F	3.4	3.07E-06	6.70E-06	0.46
10	718.9473	G	3.4	3.39E-04	6.60E-01	0.00
30	4859.543	G	3.4	2.29E-03	1.80E-01	0.01
100	3345.784	G	3.4	1.58E-03	2.00E-02	0.08
300	691.0891	G	3.4	3.26E-04	2.40E-03	0.14
1000	101.8673	G	3.4	4.81E-05	2.60E-04	0.18
3000	26.79799	G	3.4	1.26E-05	4.80E-05	0.26
10,000	6.50509	G	3.4	3.07E-06	1.40E-05	0.22
10	10928.13	C	10.0	5.16E-03	1.70E-02	0.30
30	1553.933	C	10.0	7.33E-04	1.90E-03	0.39
100	171.3441	C	10.0	8.09E-05	1.70E-04	0.48
300	28.58356	C	10.0	1.35E-05	2.70E-05	0.50
1000	4.69221	C	10.0	2.21E-06	3.70E-06	0.60
3000	0.67624	C	10.0	3.19E-07	5.40E-07	0.59
10,000	0.07718	C	10.0	3.64E-08	8.40E-08	0.43
10	21878.76	D	10.0	1.03E-02	3.10E-02	0.33
30	3524.326	D	10.0	1.66E-03	3.50E-03	0.48
100	415.6107	D	10.0	1.96E-04	3.40E-04	0.58
300	59.35934	D	10.0	2.80E-05	4.60E-05	0.61
1000	11.46665	D	10.0	5.41E-06	8.70E-06	0.62
3000	2.48115	D	10.0	1.17E-06	1.80E-06	0.65
10,000	0.42742	D	10.0	2.02E-07	3.50E-07	0.58

Table I.7 (cont.)

Distance (m)	ISC 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	ISC Conc. Fraction	Droppo Conc. Fraction	Ratio: ISC to Droppo
10	32753.36	E	10.0	1.55E-02	7.70E-02	0.20
30	5859.729	E	10.0	2.77E-03	9.30E-03	0.30
100	730.4321	E	10.0	3.45E-04	8.60E-04	0.40
300	108.2494	E	10.0	5.11E-05	1.00E-04	0.51
1000	18.72065	E	10.0	8.84E-06	1.50E-05	0.59
3000	4.71154	E	10.0	2.22E-06	3.60E-06	0.62
10,000	0.94621	E	10.0	4.47E-07	9.00E-07	0.50
10	5790.15	C	20.0	2.73E-03	8.50E-03	0.32
30	783.8774	C	20.0	3.70E-04	9.50E-04	0.39
100	85.75744	C	20.0	4.05E-05	8.70E-05	0.47
300	14.42887	C	20.0	6.81E-06	1.30E-05	0.52
1000	2.35166	C	20.0	1.11E-06	1.90E-06	0.58
3000	0.33823	C	20.0	1.60E-07	2.70E-07	0.59
10,000	0.03859	C	20.0	1.82E-08	4.20E-08	0.43
10	12297.22	D	20.0	5.80E-03	1.60E-02	0.36
30	1798.08	D	20.0	8.49E-04	1.80E-03	0.47
100	208.3232	D	20.0	9.83E-05	1.70E-04	0.58
300	29.77239	D	20.0	1.41E-05	2.30E-05	0.61
1000	5.77259	D	20.0	2.72E-06	4.40E-06	0.62
3000	1.24319	D	20.0	5.87E-07	8.90E-07	0.66
10,000	0.21382	D	20.0	1.01E-07	1.70E-07	0.59
10	19429.86	E	20.0	9.17E-03	4.00E-02	0.23
30	3026.161	E	20.0	1.43E-03	4.70E-03	0.30
100	366.7962	E	20.0	1.73E-04	4.30E-04	0.40
300	54.17096	E	20.0	2.56E-05	5.10E-05	0.50
1000	9.44989	E	20.0	4.46E-06	7.70E-06	0.58
3000	2.36646	E	20.0	1.12E-06	1.80E-06	0.62
10,000	0.4738	E	20.0	2.24E-07	4.50E-07	0.50

AERMOD Runs

Table I.8. Near Surface Vent @ 1 m³/hr Ground Level Results Using AERMOD

Distance (m)	AERMOD 1-hr Average Conc. (µg/m ³)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	6654.982	A	1.0	1.85E-06	3.9E-05	4.74E-02
30	801.7948	A	1.0	2.23E-07	4.5E-06	4.95E-02
100	57.00398	A	1.0	1.58E-08	4.0E-07	3.96E-02
300	4.02551	A	1.0	1.12E-09	4.5E-08	2.48E-02
1000	0.23735	A	1.0	6.59E-11	4.2E-09	1.57E-02
3000	0.01578	A	1.0	4.38E-12	5.1E-10	8.59E-03
10,000	0.0025	A	1.0	6.94E-13	5.7E-11	1.22E-02
10	7430.138	B	1.0	2.06E-06	8.7E-05	2.37E-02
30	950.7277	B	1.0	2.64E-07	1.0E-05	2.64E-02
100	54.56809	B	1.0	1.52E-08	9.3E-07	1.63E-02
300	3.61163	B	1.0	1.00E-09	1.0E-07	1.00E-02
1000	0.18398	B	1.0	5.11E-11	9.7E-09	5.27E-03
3000	0.01271	B	1.0	3.53E-12	1.2E-09	2.94E-03
10,000	0.00138	B	1.0	3.83E-13	1.3E-10	2.95E-03
10	4416.528	C	1.0	1.23E-06	8.7E-05	1.41E-02
30	634.526	C	1.0	1.76E-07	1.0E-05	1.76E-02
100	40.96001	C	1.0	1.14E-08	9.3E-07	1.22E-02
300	2.88304	C	1.0	8.01E-10	1.0E-07	8.01E-03
1000	0.15392	C	1.0	4.28E-11	9.7E-09	4.41E-03
3000	0.01093	C	1.0	3.04E-12	1.2E-09	2.53E-03
10,000	0.00093	C	1.0	2.58E-13	1.3E-10	1.99E-03
10	2021.717	D	1.0	5.62E-07	3.0E-04	1.87E-03
30	309.8414	D	1.0	8.61E-08	4.1E-05	2.10E-03
100	26.96017	D	1.0	7.49E-09	4.0E-06	1.87E-03
300	2.024	D	1.0	5.62E-10	5.0E-07	1.12E-03
1000	0.11722	D	1.0	3.26E-11	6.1E-08	5.34E-04
3000	0.00969	D	1.0	2.69E-12	1.1E-08	2.45E-04
10,000	0.00089	D	1.0	2.47E-13	2.1E-09	1.18E-04
10	1576.225	E	1.0	4.38E-07	5.5E-04	7.96E-04
30	283.1306	E	1.0	7.86E-08	9.9E-05	7.94E-04
100	29.93653	E	1.0	8.32E-09	1.0E-05	8.32E-04
300	3.96677	E	1.0	1.10E-09	1.2E-06	9.18E-04
1000	0.49821	E	1.0	1.38E-10	1.3E-07	1.06E-03
3000	0.08828	E	1.0	2.45E-11	2.4E-08	1.02E-03
10,000	0.01689	E	1.0	4.69E-12	5.6E-09	8.38E-04

Table I.8 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	1913.9	F	1.0	5.32E-07	1.4E-03	3.80E-04
30	373.1718	F	1.0	1.04E-07	2.2E-04	4.71E-04
100	44.36089	F	1.0	1.23E-08	2.8E-05	4.40E-04
300	6.5298	F	1.0	1.81E-09	3.4E-06	5.33E-04
1000	0.88305	F	1.0	2.45E-10	3.8E-07	6.46E-04
3000	0.1601	F	1.0	4.45E-11	6.7E-08	6.64E-04
10,000	0.03044	F	1.0	8.46E-12	1.6E-08	5.28E-04
10	3534.529	G	1.0	9.82E-07	3.9E-03	2.52E-04
30	783.9274	G	1.0	2.18E-07	4.6E-04	4.73E-04
100	120.6212	G	1.0	3.35E-08	7.0E-05	4.79E-04
300	19.67714	G	1.0	5.47E-09	9.3E-06	5.88E-04
1000	2.75407	G	1.0	7.65E-10	1.0E-06	7.65E-04
3000	0.49426	G	1.0	1.37E-10	1.9E-07	7.23E-04
10,000	0.08967	G	1.0	2.49E-11	4.4E-08	5.66E-04
10	2065.755	A	3.4	5.74E-07	1.2E-05	4.78E-02
30	253.8085	A	3.4	7.05E-08	1.3E-06	5.42E-02
100	13.55735	A	3.4	3.77E-09	1.2E-07	3.14E-02
300	0.74498	A	3.4	2.07E-10	1.3E-08	1.59E-02
1000	0.03791	A	3.4	1.05E-11	1.2E-09	8.78E-03
3000	0.00371	A	3.4	1.03E-12	1.5E-10	6.87E-03
10,000	0.00039	A	3.4	1.08E-13	1.7E-11	6.37E-03
10	2203.391	B	3.4	6.12E-07	2.5E-05	2.45E-02
30	279.8799	B	3.4	7.77E-08	3.0E-06	2.59E-02
100	16.04523	B	3.4	4.46E-09	2.7E-07	1.65E-02
300	1.06098	B	3.4	2.95E-10	3.1E-08	9.51E-03
1000	0.05361	B	3.4	1.49E-11	2.8E-09	5.32E-03
3000	0.0036	B	3.4	1.00E-12	3.4E-10	2.94E-03
10,000	0.00036	B	3.4	1.00E-13	3.8E-11	2.63E-03
10	1312.423	C	3.4	3.65E-07	5.2E-05	7.01E-03
30	186.7135	C	3.4	5.19E-08	6.5E-06	7.98E-03
100	12.02251	C	3.4	3.34E-09	6.0E-07	5.57E-03
300	0.84236	C	3.4	2.34E-10	6.9E-08	3.39E-03
1000	0.04415	C	3.4	1.23E-11	6.8E-09	1.80E-03
3000	0.00296	C	3.4	8.22E-13	9.5E-10	8.65E-04
10,000	0.00021	C	3.4	5.83E-14	1.4E-10	4.17E-04

Table I.8 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	600.2724	D	3.4	1.67E-07	8.7E-05	1.92E-03
30	90.96438	D	3.4	2.53E-08	1.2E-05	2.11E-03
100	7.87414	D	3.4	2.19E-09	1.2E-06	1.82E-03
300	0.58368	D	3.4	1.62E-10	1.5E-07	1.08E-03
1000	0.03216	D	3.4	8.93E-12	1.8E-08	4.96E-04
3000	0.00232	D	3.4	6.44E-13	3.2E-09	2.01E-04
10,000	0.00016	D	3.4	4.44E-14	6.1E-10	7.29E-05
10	330.2244	E	3.4	9.17E-08	1.6E-04	5.73E-04
30	59.25088	E	3.4	1.65E-08	2.9E-05	5.68E-04
100	6.24029	E	3.4	1.73E-09	3.0E-06	5.78E-04
300	0.8187	E	3.4	2.27E-10	3.5E-07	6.50E-04
1000	0.09955	E	3.4	2.77E-11	3.9E-08	7.09E-04
3000	0.01634	E	3.4	4.54E-12	7.0E-09	6.48E-04
10,000	0.00267	E	3.4	7.42E-13	1.6E-09	4.64E-04
10	308.1021	F	3.4	8.56E-08	4.1E-04	2.09E-04
30	60.08195	F	3.4	1.67E-08	6.6E-05	2.53E-04
100	7.12244	F	3.4	1.98E-09	8.1E-06	2.44E-04
300	1.04134	F	3.4	2.89E-10	9.9E-07	2.92E-04
1000	0.13778	F	3.4	3.83E-11	1.1E-07	3.48E-04
3000	0.02374	F	3.4	6.59E-12	2.0E-08	3.30E-04
10,000	0.0041	F	3.4	1.14E-12	4.6E-09	2.48E-04
10	242.9404	G	3.4	6.75E-08	1.1E-03	6.13E-05
30	54.16738	G	3.4	1.50E-08	1.3E-04	1.16E-04
100	8.35894	G	3.4	2.32E-09	2.1E-05	1.11E-04
300	1.37349	G	3.4	3.82E-10	2.7E-06	1.41E-04
1000	0.19683	G	3.4	5.47E-11	3.1E-07	1.76E-04
3000	0.03738	G	3.4	1.04E-11	5.5E-08	1.89E-04
10,000	0.00773	G	3.4	2.15E-12	1.3E-08	1.65E-04
10	187.2918	C	10.0	5.20E-08	1.8E-05	2.89E-03
30	26.88572	C	10.0	7.47E-09	2.2E-06	3.39E-03
100	2.16424	C	10.0	6.01E-10	2.0E-07	3.01E-03
300	0.15904	C	10.0	4.42E-11	2.3E-08	1.92E-03
1000	0.00802	C	10.0	2.23E-12	2.3E-09	9.69E-04
3000	0.00057	C	10.0	1.58E-13	3.2E-10	4.95E-04
10,000	0.00004	C	10.0	1.11E-14	4.9E-11	2.27E-04

Table I.8 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	187.8382	D	10.0	5.22E-08	3.0E-05	1.74E-03
30	27.89001	D	10.0	7.75E-09	4.1E-06	1.89E-03
100	2.35602	D	10.0	6.54E-10	4.0E-07	1.64E-03
300	0.17146	D	10.0	4.76E-11	5.0E-08	9.53E-04
1000	0.00928	D	10.0	2.58E-12	6.1E-09	4.23E-04
3000	0.00064	D	10.0	1.78E-13	1.1E-09	1.62E-04
10,000	0.00004	D	10.0	1.11E-14	2.1E-10	5.29E-05
10	109.8922	E	10.0	3.05E-08	5.5E-05	5.55E-04
30	19.54657	E	10.0	5.43E-09	9.9E-06	5.48E-04
100	2.04931	E	10.0	5.69E-10	1.0E-06	5.69E-04
300	0.26737	E	10.0	7.43E-11	1.2E-07	6.19E-04
1000	0.03193	E	10.0	8.87E-12	1.3E-08	6.82E-04
3000	0.00499	E	10.0	1.39E-12	2.4E-09	5.78E-04
10,000	0.00071	E	10.0	1.97E-13	5.6E-10	3.52E-04
10	66.64723	C	20.0	1.85E-08	8.8E-06	2.10E-03
30	9.6467	C	20.0	2.68E-09	1.1E-06	2.44E-03
100	0.88262	C	20.0	2.45E-10	1.0E-07	2.45E-03
300	0.06629	C	20.0	1.84E-11	1.2E-08	1.53E-03
1000	0.00318	C	20.0	8.83E-13	1.2E-09	7.36E-04
3000	0.00019	C	20.0	5.28E-14	1.6E-10	3.30E-04
10,000	0.00002	C	20.0	5.56E-15	2.5E-11	2.22E-04
10	63.55089	D	20.0	1.77E-08	1.5E-05	1.18E-03
30	9.53857	D	20.0	2.65E-09	2.0E-06	1.32E-03
100	0.88242	D	20.0	2.45E-10	2.0E-07	1.23E-03
300	0.0711	D	20.0	1.98E-11	2.5E-08	7.90E-04
1000	0.00398	D	20.0	1.11E-12	3.1E-09	3.57E-04
3000	0.00029	D	20.0	8.06E-14	5.5E-10	1.46E-04
10,000	0.00002	D	20.0	5.56E-15	1.0E-10	5.56E-05
10	54.93183	E	20.0	1.53E-08	2.8E-05	5.45E-04
30	9.76893	E	20.0	2.71E-09	4.9E-06	5.54E-04
100	1.02372	E	20.0	2.84E-10	5.0E-07	5.69E-04
300	0.1334	E	20.0	3.71E-11	6.0E-08	6.18E-04
1000	0.01586	E	20.0	4.41E-12	6.7E-09	6.58E-04
3000	0.00245	E	20.0	6.81E-13	1.2E-09	5.67E-04
10,000	0.00034	E	20.0	9.44E-14	2.8E-10	3.37E-04

Table I.9. AP Farm 6 m Vent @ 1359 m³/hr Ground Level Results Using AERMOD

Distance (m)	AERMOD 1-hr Average Conc. (µg/m ³)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	0.0265	A	1.0	1.00E-08	1.30E-03	7.70E-06
30	22.39979	A	1.0	8.46E-06	3.70E-03	2.29E-03
100	46.86	A	1.0	1.77E-05	5.20E-04	3.40E-02
300	3.82632	A	1.0	1.44E-06	6.10E-05	2.37E-02
1000	0.21911	A	1.0	8.27E-08	5.70E-06	1.45E-02
3000	0.01424	A	1.0	5.38E-09	6.90E-07	7.79E-03
10,000	0.00206	A	1.0	7.78E-10	7.70E-08	1.01E-02
10	0.00286	B	1.0	1.08E-09	1.10E-05	9.82E-05
30	4.27051	B	1.0	1.61E-06	3.70E-03	4.36E-04
100	24.43854	B	1.0	9.23E-06	1.10E-03	8.39E-03
300	3.32589	B	1.0	1.26E-06	1.40E-04	8.97E-03
1000	0.16972	B	1.0	6.41E-08	1.30E-05	4.93E-03
3000	0.01145	B	1.0	4.32E-09	1.60E-06	2.70E-03
10,000	0.00112	B	1.0	4.23E-10	1.80E-07	2.35E-03
10	0.00043	C	1.0	1.62E-10	4.90E-10	3.31E-01
30	0.96534	C	1.0	3.64E-07	2.00E-03	1.82E-04
100	10.76325	C	1.0	4.06E-06	2.10E-03	1.93E-03
300	2.32196	C	1.0	8.77E-07	3.10E-04	2.83E-03
1000	0.14148	C	1.0	5.34E-08	3.10E-05	1.72E-03
3000	0.00995	C	1.0	3.76E-09	4.40E-06	8.54E-04
10,000	0.00079	C	1.0	2.98E-10	6.70E-07	4.45E-04
10	0.00005	D	1.0	1.89E-11	1.50E-16	1.26E+05
30	0.19734	D	1.0	7.45E-08	5.30E-04	1.41E-04
100	3.53316	D	1.0	1.33E-06	3.10E-03	4.30E-04
300	1.08706	D	1.0	4.10E-07	6.30E-04	6.51E-04
1000	0.09069	D	1.0	3.42E-08	8.20E-05	4.18E-04
3000	0.0082	D	1.0	3.10E-09	1.50E-05	2.06E-04
10,000	0.00076	D	1.0	2.87E-10	2.80E-06	1.02E-04
10	0	E	1.0	0.00E+00	0.00E+00	
30	17.09716	E	1.0	6.45E-06	1.30E-08	4.96E+02
100	18.69299	E	1.0	7.06E-06	2.00E-03	3.53E-03
300	3.15496	E	1.0	1.19E-06	1.30E-03	9.16E-04
1000	0.41405	E	1.0	1.56E-07	1.80E-04	8.68E-04
3000	0.07503	E	1.0	2.83E-08	3.20E-05	8.85E-04
10,000	0.01487	E	1.0	5.61E-09	7.50E-06	7.48E-04
10	0	F	1.0	0.00E+00	0.00E+00	
30	5.41967	F	1.0	2.05E-06	3.50E-25	5.85E+18
100	21.50296	F	1.0	8.12E-06	1.20E-04	6.76E-02
300	4.69552	F	1.0	1.77E-06	1.90E-03	9.33E-04

Table I.9 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
1000	0.69045	F	1.0	2.61E-07	4.50E-04	5.79E-04
3000	0.12957	F	1.0	4.89E-08	8.80E-05	5.56E-04
10,000	0.02583	F	1.0	9.75E-09	2.10E-05	4.64E-04
10	0.00282	A	3.4	1.06E-09	3.80E-04	2.80E-06
30	21.20282	A	3.4	8.00E-06	1.10E-03	7.28E-03
100	10.95401	A	3.4	4.14E-06	1.50E-04	2.76E-02
300	0.68819	A	3.4	2.60E-07	1.80E-05	1.44E-02
1000	0.03416	A	3.4	1.29E-08	1.70E-06	7.59E-03
3000	0.00338	A	3.4	1.28E-09	2.00E-07	6.38E-03
10,000	0.00033	A	3.4	1.25E-10	2.30E-08	5.42E-03
10	0.0004	B	3.4	1.51E-10	3.40E-06	4.44E-05
30	12.36484	B	3.4	4.67E-06	1.10E-03	4.24E-03
100	12.35115	B	3.4	4.66E-06	3.30E-04	1.41E-02
300	0.99406	B	3.4	3.75E-07	4.10E-05	9.15E-03
1000	0.04823	B	3.4	1.82E-08	3.90E-06	4.67E-03
3000	0.00319	B	3.4	1.20E-09	4.70E-07	2.56E-03
10,000	0.00029	B	3.4	1.09E-10	5.20E-08	2.11E-03
10	0.00001	C	3.4	3.78E-12	1.60E-10	2.36E-02
30	2.9022	C	3.4	1.10E-06	5.80E-04	1.89E-03
100	7.05776	C	3.4	2.66E-06	6.10E-04	4.37E-03
300	0.74424	C	3.4	2.81E-07	9.00E-05	3.12E-03
1000	0.03945	C	3.4	1.49E-08	9.20E-06	1.62E-03
3000	0.00263	C	3.4	9.93E-10	1.30E-06	7.64E-04
10,000	0.00018	C	3.4	6.80E-11	2.00E-07	3.40E-04
10	0	D	3.4	0.00E+00	5.30E-17	0.00E+00
30	0.42892	D	3.4	1.62E-07	1.60E-04	1.62E-07
100	2.99224	D	3.4	1.13E-06	9.00E-04	1.13E-06
300	0.39483	D	3.4	1.49E-07	1.80E-04	1.49E-07
1000	0.02524	D	3.4	9.53E-09	2.40E-05	9.53E-09
3000	0.00189	D	3.4	7.13E-10	4.40E-06	7.13E-10
10,000	0.00013	D	3.4	4.91E-11	8.30E-07	4.91E-11
10	0	E	3.4	0.00E+00	0.00E+00	
30	3.62199	E	3.4	1.37E-06	3.90E-09	3.51E+02
100	3.90505	E	3.4	1.47E-06	5.90E-04	2.50E-03
300	0.65119	E	3.4	2.46E-07	3.70E-04	6.64E-04
1000	0.08237	E	3.4	3.11E-08	5.20E-05	5.98E-04
3000	0.0137	E	3.4	5.17E-09	9.40E-06	5.50E-04
10,000	0.00229	E	3.4	8.64E-10	2.20E-06	3.93E-04

Table I.9 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	0	F	3.4	0.00E+00	0.00E+00	
30	0.86871	F	3.4	3.28E-07	1.20E-25	2.73E+18
100	3.4453	F	3.4	1.30E-06	3.40E-05	3.83E-02
300	0.74649	F	3.4	2.82E-07	5.50E-04	5.12E-04
1000	0.10694	F	3.4	4.04E-08	1.30E-04	3.11E-04
3000	0.0189	F	3.4	7.13E-09	2.60E-05	2.74E-04
10,000	0.00337	F	3.4	1.27E-09	6.20E-06	2.05E-04
10	0	G	3.4	0.00E+00	0.00E+00	
30	0.00003	G	3.4	1.13E-11	0.00E+00	
100	0.83394	G	3.4	3.15E-07	2.10E-10	1.50E+03
300	0.61024	G	3.4	2.30E-07	2.20E-04	1.05E-03
1000	0.1243	G	3.4	4.69E-08	2.80E-04	1.68E-04
3000	0.02605	G	3.4	9.83E-09	6.70E-05	1.47E-04
10,000	0.00582	G	3.4	2.20E-09	1.70E-05	1.29E-04
10	0	C	10.0	0.00E+00	5.40E-11	0.00E+00
30	2.61458	C	10.0	9.87E-07	2.00E-04	4.94E-03
100	1.54431	C	10.0	5.83E-07	2.10E-04	2.78E-03
300	0.14548	C	10.0	5.49E-08	3.10E-05	1.77E-03
1000	0.00789	C	10.0	2.98E-09	3.10E-06	9.61E-04
3000	0.00057	C	10.0	2.15E-10	4.40E-07	4.89E-04
10,000	0.00004	C	10.0	1.51E-11	6.70E-08	2.25E-04
10	0	D	10.0	0.00E+00	1.90E-17	0.00E+00
30	1.69819	D	10.0	6.41E-07	5.40E-05	1.19E-02
100	1.52125	D	10.0	5.74E-07	3.10E-04	1.85E-03
300	0.14807	D	10.0	5.59E-08	6.30E-05	8.87E-04
1000	0.00878	D	10.0	3.31E-09	8.20E-06	4.04E-04
3000	0.00061	D	10.0	2.30E-10	1.50E-06	1.54E-04
10,000	0.00004	D	10.0	1.51E-11	2.80E-07	5.39E-05
10	0	E	10.0	0.00E+00	0.00E+00	
30	1.9924	E	10.0	7.52E-07	1.40E-09	5.37E+02
100	1.46402	E	10.0	5.53E-07	2.00E-04	2.76E-03
300	0.23547	E	10.0	8.89E-08	1.30E-04	6.84E-04
1000	0.02904	E	10.0	1.10E-08	1.80E-05	6.09E-04
3000	0.00457	E	10.0	1.73E-09	3.20E-06	5.39E-04
10,000	0.00066	E	10.0	2.49E-10	7.50E-07	3.32E-04
10	0	C	20.0	0.00E+00	2.70E-11	0.00E+00
30	1.51771	C	20.0	5.73E-07	9.90E-05	5.79E-03
100	0.62283	C	20.0	2.35E-07	1.00E-04	2.35E-03
300	0.05894	C	20.0	2.22E-08	1.50E-05	1.48E-03

Table I.9 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
1000	0.00311	C	20.0	1.17E-09	1.60E-06	7.34E-04
3000	0.00019	C	20.0	7.17E-11	2.20E-07	3.26E-04
10,000	0.00002	C	20.0	7.55E-12	3.30E-08	2.29E-04
10	0	D	20.0	0.00E+00	9.50E-18	0.00E+00
30	0.98505	D	20.0	3.72E-07	2.70E-05	1.38E-02
100	0.59436	D	20.0	2.24E-07	1.50E-04	1.50E-03
300	0.05871	D	20.0	2.22E-08	3.10E-05	7.15E-04
1000	0.00366	D	20.0	1.38E-09	4.10E-06	3.37E-04
3000	0.00027	D	20.0	1.02E-10	7.40E-07	1.38E-04
10,000	0.00002	D	20.0	7.55E-12	1.40E-07	5.39E-05
10	0	E	20.0	0.00E+00	0.00E+00	
30	0.99968	E	20.0	3.77E-07	6.80E-10	5.55E+02
100	0.73207	E	20.0	2.76E-07	1.00E-04	2.76E-03
300	0.11757	E	20.0	4.44E-08	6.30E-05	7.04E-04
1000	0.01444	E	20.0	5.45E-09	8.80E-06	6.19E-04
3000	0.00224	E	20.0	8.46E-10	1.60E-06	5.29E-04
10,000	0.00031	E	20.0	1.17E-10	3.80E-07	3.08E-04

Table I.10. AP Farm 6 m Vent @ 1359 m³/hr Plume Centerline Results Using AERMOD

Distance (m)	AERMOD 1-hr Average Conc. (µg/m ³)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	118.5789	A	1.0	4.48E-05	2.70E-02	1.66E-03
30	132.7704	A	1.0	5.01E-05	3.40E-03	1.47E-02
100	39.95056	A	1.0	1.51E-05	5.00E-04	3.02E-02
300	3.55918	A	1.0	1.34E-06	6.10E-05	2.20E-02
1000	0.21035	A	1.0	7.94E-08	5.70E-06	1.39E-02
3000	0.01404	A	1.0	5.30E-09	6.90E-07	7.68E-03
10,000	0.00205	A	1.0	7.74E-10	7.70E-08	1.01E-02
1	124.9581	B	1.0	4.72E-05	8.60E-01	5.49E-05
3	47.40843	B	1.0	1.79E-05	4.10E-01	4.37E-05
10	40.99585	B	1.0	1.55E-05	5.90E-02	2.62E-04
30	51.89075	B	1.0	1.96E-05	6.90E-03	2.84E-03
100	20.41649	B	1.0	7.71E-06	1.00E-03	7.71E-03
300	2.97398	B	1.0	1.12E-06	1.40E-04	8.02E-03
1000	0.16234	B	1.0	6.13E-08	1.30E-05	4.71E-03
3000	0.01123	B	1.0	4.24E-09	1.60E-06	2.65E-03
10,000	0.00112	B	1.0	4.23E-10	1.80E-07	2.35E-03
10	13.4708	C	1.0	5.09E-06	4.90E-10	1.04E+04
30	17.79763	C	1.0	6.72E-06	2.00E-03	3.36E-03
100	9.33712	C	1.0	3.52E-06	2.10E-03	1.68E-03
300	1.99114	C	1.0	7.52E-07	3.10E-04	2.42E-03
1000	0.13348	C	1.0	5.04E-08	3.10E-05	1.63E-03
3000	0.00967	C	1.0	3.65E-09	4.40E-06	8.30E-04
10,000	0.00079	C	1.0	2.98E-10	6.70E-07	4.45E-04
10	3.11866	D	1.0	1.18E-06	2.00E-01	5.89E-06
30	3.93268	D	1.0	1.48E-06	2.80E-02	5.30E-05
100	2.96964	D	1.0	1.12E-06	3.00E-03	3.74E-04
300	0.85382	D	1.0	3.22E-07	5.90E-04	5.46E-04
1000	0.08311	D	1.0	3.14E-08	8.10E-05	3.87E-04
3000	0.00792	D	1.0	2.99E-09	1.50E-05	1.99E-04
10,000	0.00075	D	1.0	2.83E-10	2.80E-06	1.01E-04
10	747.7154	E	1.0	2.82E-04	4.00E-01	7.06E-04
30	85.41246	E	1.0	3.22E-05	7.00E-02	4.61E-04
100	9.83646	E	1.0	3.71E-06	6.90E-03	5.38E-04
300	1.96117	E	1.0	7.40E-07	1.10E-03	6.73E-04
1000	0.27927	E	1.0	1.05E-07	1.70E-04	6.20E-04
3000	0.05314	E	1.0	2.01E-08	3.20E-05	6.27E-04
10,000	0.01135	E	1.0	4.28E-09	7.50E-06	5.71E-04

Table I.10 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	874.9922	F	1.0	3.30E-04	6.50E-01	5.08E-04
30	104.4644	F	1.0	3.94E-05	1.70E-01	2.32E-04
100	11.70609	F	1.0	4.42E-06	1.90E-02	2.33E-04
300	2.56875	F	1.0	9.70E-07	2.40E-03	4.04E-04
1000	0.43445	F	1.0	1.64E-07	4.20E-04	3.90E-04
3000	0.08738	F	1.0	3.30E-08	8.60E-05	3.84E-04
10,000	0.01901	F	1.0	7.18E-09	2.10E-05	3.42E-04
10	242.7207	A	3.4	9.16E-05	8.00E-03	1.15E-02
30	64.64366	A	3.4	2.44E-05	1.00E-03	2.44E-02
100	8.735	A	3.4	3.30E-06	1.50E-04	2.20E-02
300	0.64643	A	3.4	2.44E-07	1.80E-05	1.36E-02
1000	0.03334	A	3.4	1.26E-08	1.70E-06	7.40E-03
3000	0.00332	A	3.4	1.25E-09	2.00E-07	6.27E-03
10,000	0.00033	A	3.4	1.25E-10	2.30E-08	5.42E-03
10	199.2006	B	3.4	7.52E-05	1.80E-02	4.18E-03
30	62.95585	B	3.4	2.38E-05	2.10E-03	1.13E-02
100	9.03532	B	3.4	3.41E-06	3.00E-04	1.14E-02
300	0.88807	B	3.4	3.35E-07	4.00E-05	8.38E-03
1000	0.04612	B	3.4	1.74E-08	3.90E-06	4.46E-03
3000	0.00312	B	3.4	1.18E-09	4.70E-07	2.51E-03
10,000	0.00028	B	3.4	1.06E-10	5.20E-08	2.03E-03
10	72.49843	C	3.4	2.74E-05	3.90E-02	7.02E-04
30	32.50785	C	3.4	1.23E-05	4.50E-03	2.73E-03
100	4.9696	C	3.4	1.88E-06	5.40E-04	3.47E-03
300	0.6402	C	3.4	2.42E-07	8.80E-05	2.75E-03
1000	0.03721	C	3.4	1.40E-08	9.20E-06	1.53E-03
3000	0.00255	C	3.4	9.63E-10	1.30E-06	7.40E-04
10,000	0.00018	C	3.4	6.80E-11	2.00E-07	3.40E-04
10	16.18822	D	3.4	6.11E-06	6.90E-02	8.86E-05
30	11.39559	D	3.4	4.30E-06	8.30E-03	5.18E-04
100	2.00033	D	3.4	7.55E-07	8.70E-04	8.68E-04
300	0.31841	D	3.4	1.20E-07	1.70E-04	7.07E-04
1000	0.02313	D	3.4	8.73E-09	2.40E-05	3.64E-04
3000	0.00182	D	3.4	6.87E-10	4.30E-06	1.60E-04
10,000	0.00013	D	3.4	4.91E-11	8.30E-07	5.91E-05

Table I.10 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	156.7993	E	3.4	5.92E-05	1.60E-01	3.70E-04
30	17.88428	E	3.4	6.75E-06	2.20E-02	3.07E-04
100	2.05052	E	3.4	7.74E-07	2.00E-03	3.87E-04
300	0.40276	E	3.4	1.52E-07	3.30E-04	4.61E-04
1000	0.05473	E	3.4	2.07E-08	5.00E-05	4.13E-04
3000	0.00938	E	3.4	3.54E-09	9.30E-06	3.81E-04
10,000	0.00164	E	3.4	6.19E-10	2.20E-06	2.81E-04
10	140.7405	F	3.4	5.31E-05	3.60E-01	1.48E-04
30	16.78352	F	3.4	6.34E-06	5.80E-02	1.09E-04
100	1.873	F	3.4	7.07E-07	5.70E-03	1.24E-04
300	0.40646	F	3.4	1.53E-07	7.00E-04	2.19E-04
1000	0.06639	F	3.4	2.51E-08	1.20E-04	2.09E-04
3000	0.01237	F	3.4	4.67E-09	2.50E-05	1.87E-04
10,000	0.00236	F	3.4	8.91E-10	6.10E-06	1.46E-04
1	72.34089	C	10.0	2.73E-05	5.80E-01	4.71E-05
3	108.9677	C	10.0	4.11E-05	1.30E-01	3.16E-04
10	53.65137	C	10.0	2.03E-05	1.30E-02	1.56E-03
30	8.3446	C	10.0	3.15E-06	1.50E-03	2.10E-03
100	1.06514	C	10.0	4.02E-07	1.80E-04	2.23E-03
300	0.12537	C	10.0	4.73E-08	3.00E-05	1.58E-03
1000	0.00748	C	10.0	2.82E-09	3.10E-06	9.11E-04
3000	0.00056	C	10.0	2.11E-10	4.40E-07	4.80E-04
10,000	0.00004	C	10.0	1.51E-11	6.70E-08	2.25E-04
10	47.46299	D	10.0	1.79E-05	2.50E-02	7.17E-04
30	8.0211	D	10.0	3.03E-06	2.80E-03	1.08E-03
100	0.97677	D	10.0	3.69E-07	3.00E-04	1.23E-03
300	0.12237	D	10.0	4.62E-08	5.90E-05	7.83E-04
1000	0.0081	D	10.0	3.06E-09	8.10E-06	3.78E-04
3000	0.00059	D	10.0	2.23E-10	1.50E-06	1.48E-04
10,000	0.00003	D	10.0	1.13E-11	2.80E-07	4.04E-05
10	56.85279	E	10.0	2.45E-06	7.40E-03	3.31E-04
30	6.47961	E	10.0	2.90E-07	6.90E-04	4.20E-04
100	0.76754	E	10.0	5.53E-08	1.10E-04	5.03E-04
300	0.14647	E	10.0	7.24E-09	1.70E-05	4.26E-04
1000	0.01917	E	10.0	1.16E-09	3.20E-06	3.61E-04
3000	0.00306	E	10.0	1.70E-10	7.50E-07	2.27E-04
10,000	0.00045	E	10.0	2.36E-04	4.30E-01	5.49E-04

Table I.10 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	26.42967	C	20.0	9.98E-06	6.80E-03	1.47E-03
30	3.29081	C	20.0	1.24E-06	7.60E-04	1.63E-03
100	0.42034	C	20.0	1.59E-07	9.20E-05	1.72E-03
300	0.04968	C	20.0	1.88E-08	1.50E-05	1.25E-03
1000	0.00293	C	20.0	1.11E-09	1.60E-06	6.91E-04
3000	0.00018	C	20.0	6.80E-11	2.20E-07	3.09E-04
10,000	0.00002	C	20.0	7.55E-12	3.30E-08	2.29E-04
10	23.68004	D	20.0	8.94E-06	1.20E-02	7.45E-04
30	3.05799	D	20.0	1.15E-06	1.40E-03	8.25E-04
100	0.37177	D	20.0	1.40E-07	1.50E-04	9.36E-04
300	0.04728	D	20.0	1.78E-08	2.90E-05	6.15E-04
1000	0.00331	D	20.0	1.25E-09	4.10E-06	3.05E-04
3000	0.00026	D	20.0	9.82E-11	7.40E-07	1.33E-04
10,000	0.00002	D	20.0	7.55E-12	1.40E-07	5.39E-05
10	28.43576	E	20.0	1.07E-05	3.20E-02	3.35E-04
30	3.24034	E	20.0	1.22E-06	3.70E-03	3.31E-04
100	0.38372	E	20.0	1.45E-07	3.50E-04	4.14E-04
300	0.07309	E	20.0	2.76E-08	5.50E-05	5.02E-04
1000	0.00951	E	20.0	3.59E-09	8.50E-06	4.22E-04
3000	0.0015	E	20.0	5.66E-10	1.60E-06	3.54E-04
10,000	0.00021	E	20.0	7.93E-11	3.80E-07	2.09E-04

Table I.11. AY Farm 16.7 m Vent @ 1699 m³/hr Ground Level Results Using AERMOD

Distance (m)	AERMOD 1-hr Average Conc. (µg/m ³)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	0	A	1.0	0.00E+00	1.10E-15	0.00E+00
30	0.40193	A	1.0	1.90E-07	1.70E-04	1.12E-03
100	36.17548	A	1.0	1.71E-05	4.80E-04	3.56E-02
300	4.38763	A	1.0	2.07E-06	7.40E-05	2.80E-02
1000	0.28688	A	1.0	1.35E-07	7.10E-06	1.91E-02
3000	0.01874	A	1.0	8.84E-09	8.60E-07	1.03E-02
10,000	0.00323	A	1.0	1.52E-09	9.70E-08	1.57E-02
10	0	B	1.0	0.00E+00	2.40E-39	0.00E+00
30	0.00282	B	1.0	1.33E-09	6.40E-07	2.08E-03
100	15.93228	B	1.0	7.52E-06	5.90E-04	1.27E-02
300	4.12225	B	1.0	1.95E-06	1.60E-04	1.22E-02
1000	0.22447	B	1.0	1.06E-07	1.60E-05	6.62E-03
3000	0.01479	B	1.0	6.98E-09	2.00E-06	3.49E-03
10,000	0.00174	B	1.0	8.21E-10	2.20E-07	3.73E-03
10	0	C	1.0	0.00E+00	0.00E+00	
30	0.00001	C	1.0	4.72E-12	7.10E-12	6.65E-01
100	4.21703	C	1.0	1.99E-06	3.80E-04	5.24E-03
300	2.90438	C	1.0	1.37E-06	3.10E-04	4.42E-03
1000	0.18417	C	1.0	8.69E-08	3.80E-05	2.29E-03
3000	0.01251	C	1.0	5.90E-09	5.40E-06	1.09E-03
10,000	0.00111	C	1.0	5.24E-10	8.40E-07	6.24E-04
10	0	D	1.0	0.00E+00	0.00E+00	
30	0	D	1.0	0.00E+00	1.40E-19	0.00E+00
100	0.52685	D	1.0	2.49E-07	8.50E-05	2.93E-03
300	1.27985	D	1.0	6.04E-07	4.50E-04	1.34E-03
1000	0.12214	D	1.0	5.76E-08	9.40E-05	6.13E-04
3000	0.01063	D	1.0	5.02E-09	1.80E-05	2.79E-04
10,000	0.00097	D	1.0	4.58E-10	3.50E-06	1.31E-04
10	0	E	1.0	0.00E+00	0.00E+00	
30	0	E	1.0	0.00E+00	0.00E+00	
100	2.09946	E	1.0	9.91E-07	3.80E-09	2.61E+02
300	2.43683	E	1.0	1.15E-06	2.70E-04	4.26E-03
1000	0.40627	E	1.0	1.92E-07	1.70E-04	1.13E-03
3000	0.0761	E	1.0	3.59E-08	3.80E-05	9.45E-04
10,000	0.01513	E	1.0	7.14E-09	9.20E-06	7.76E-04
10	0	F	1.0	0.00E+00	0.00E+00	
30	0	F	1.0	0.00E+00	0.00E+00	
100	0.32016	F	1.0	1.51E-07	1.00E-24	1.51E+17
300	2.91397	F	1.0	1.38E-06	5.60E-06	2.46E-01

Table I.11 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
1000	0.67518	F	1.0	3.19E-07	2.50E-04	1.27E-03
3000	0.13617	F	1.0	6.43E-08	9.10E-05	7.06E-04
10,000	0.02725	F	1.0	1.29E-08	2.40E-05	5.36E-04
10	0	A	3.4	0.00E+00	3.20E-16	0.00E+00
30	0.04886	A	3.4	2.31E-08	4.90E-05	4.71E-04
100	9.81425	A	3.4	4.63E-06	1.40E-04	3.31E-02
300	0.84172	A	3.4	3.97E-07	2.20E-05	1.81E-02
1000	0.05009	A	3.4	2.36E-08	2.10E-06	1.13E-02
3000	0.00436	A	3.4	2.06E-09	2.50E-07	8.23E-03
10,000	0.00051	A	3.4	2.41E-10	2.80E-08	8.60E-03
10	0	B	3.4	0.00E+00	7.60E-40	0.00E+00
30	0.00968	B	3.4	4.57E-09	1.90E-07	2.40E-02
100	8.13553	B	3.4	3.84E-06	1.70E-04	2.26E-02
300	1.23926	B	3.4	5.85E-07	4.70E-05	1.24E-02
1000	0.06432	B	3.4	3.04E-08	4.80E-06	6.32E-03
3000	0.00417	B	3.4	1.97E-09	5.80E-07	3.39E-03
10,000	0.00046	B	3.4	2.17E-10	6.50E-08	3.34E-03
10	0	C	3.4	0.00E+00	0.00E+00	
30	0.00002	C	3.4	9.44E-12	2.10E-12	4.49E+00
100	3.00053	C	3.4	1.42E-06	1.10E-04	1.29E-02
300	0.92465	C	3.4	4.36E-07	9.00E-05	4.85E-03
1000	0.05204	C	3.4	2.46E-08	1.10E-05	2.23E-03
3000	0.00338	C	3.4	1.60E-09	1.60E-06	9.97E-04
10,000	0.00026	C	3.4	1.23E-10	2.50E-07	4.91E-04
10	0	D	3.4	0.00E+00	0.00E+00	
30	0	D	3.4	0.00E+00	4.10E-20	0.00E+00
100	0.57608	D	3.4	2.72E-07	2.50E-05	1.09E-02
300	0.45329	D	3.4	2.14E-07	1.30E-04	1.65E-03
1000	0.03408	D	3.4	1.61E-08	2.80E-05	5.74E-04
3000	0.00256	D	3.4	1.21E-09	5.30E-06	2.28E-04
10,000	0.00017	D	3.4	8.02E-11	1.00E-06	8.02E-05
10	0	E	3.4	0.00E+00	0.00E+00	
30	0	E	3.4	0.00E+00	0.00E+00	
100	0.44315	E	3.4	2.09E-07	1.10E-09	1.90E+02
300	0.50326	E	3.4	2.38E-07	7.90E-05	3.01E-03
1000	0.08086	E	3.4	3.82E-08	5.10E-05	7.48E-04
3000	0.01392	E	3.4	6.57E-09	1.10E-05	5.97E-04
10,000	0.00233	E	3.4	1.10E-09	2.70E-06	4.07E-04

Table I.11 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	0	F	3.4	0.00E+00	0.00E+00	
30	0	F	3.4	0.00E+00	0.00E+00	
100	0.051	F	3.4	2.41E-08	3.10E-25	7.76E+16
300	0.46329	F	3.4	2.19E-07	1.60E-06	1.37E-01
1000	0.10479	F	3.4	4.95E-08	7.50E-05	6.59E-04
3000	0.01997	F	3.4	9.42E-09	2.70E-05	3.49E-04
10,000	0.00359	F	3.4	1.69E-09	7.20E-06	2.35E-04
10	0	G	3.4	0.00E+00	0.00E+00	
30	0	G	3.4	0.00E+00	0.00E+00	
100	0	G	3.4	0.00E+00	0.00E+00	
300	0.01427	G	3.4	6.73E-09	3.30E-13	2.04E+04
1000	0.08813	G	3.4	4.16E-08	2.10E-05	1.98E-03
3000	0.02638	G	3.4	1.24E-08	4.30E-05	2.90E-04
10,000	0.0063	G	3.4	2.97E-09	1.60E-05	1.86E-04
10	0	C	10.0	0.00E+00	0.00E+00	
30	0.00001	C	10.0	4.72E-12	7.20E-13	6.55E+00
100	0.75224	C	10.0	3.55E-07	3.80E-05	9.34E-03
300	0.17091	C	10.0	8.07E-08	3.10E-05	2.60E-03
1000	0.01023	C	10.0	4.83E-09	3.80E-06	1.27E-03
3000	0.00083	C	10.0	3.92E-10	5.40E-07	7.25E-04
10,000	0.00006	C	10.0	2.83E-11	8.40E-08	3.37E-04
10	0	D	10.0	0.00E+00	0.00E+00	
30	0	D	10.0	0.00E+00	1.40E-20	0.00E+00
100	0.59685	D	10.0	2.82E-07	8.60E-06	3.28E-02
300	0.17797	D	10.0	8.40E-08	4.50E-05	1.87E-03
1000	0.01197	D	10.0	5.65E-09	9.40E-06	6.01E-04
3000	0.00084	D	10.0	3.96E-10	1.80E-06	2.20E-04
10,000	0.00005	D	10.0	2.36E-11	3.50E-07	6.74E-05
10	0	E	10.0	0.00E+00	0.00E+00	
30	0	E	10.0	0.00E+00	0.00E+00	
100	0.29131	E	10.0	1.37E-07	3.80E-10	3.62E+02
300	0.19311	E	10.0	9.11E-08	2.70E-05	3.38E-03
1000	0.02902	E	10.0	1.37E-08	1.70E-05	8.06E-04
3000	0.0047	E	10.0	2.22E-09	3.80E-06	5.84E-04
10,000	0.00068	E	10.0	3.21E-10	9.20E-07	3.49E-04
10	0	C	20.0	0.00E+00	0.00E+00	
30	0	C	20.0	0.00E+00	3.60E-13	0.00E+00
100	0.32374	C	20.0	1.53E-07	1.90E-05	8.04E-03
300	0.06678	C	20.0	3.15E-08	1.50E-05	2.10E-03

Table I.11 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
1000	0.00395	C	20.0	1.86E-09	1.90E-06	9.81E-04
3000	0.00027	C	20.0	1.27E-10	2.70E-07	4.72E-04
10,000	0.00003	C	20.0	1.42E-11	4.20E-08	3.37E-04
10	0	D	20.0	0.00E+00	0.00E+00	
30	0	D	20.0	0.00E+00	7.00E-21	0.00E+00
100	0.24456	D	20.0	1.15E-07	4.30E-06	2.68E-02
300	0.06726	D	20.0	3.17E-08	2.30E-05	1.38E-03
1000	0.00491	D	20.0	2.32E-09	4.70E-06	4.93E-04
3000	0.00038	D	20.0	1.79E-10	9.10E-07	1.97E-04
10,000	0.00002	D	20.0	9.44E-12	1.80E-07	5.24E-05
10	0	E	20.0	0.00E+00	0.00E+00	
30	0	E	20.0	0.00E+00	0.00E+00	
100	0.16479	E	20.0	7.78E-08	1.90E-10	4.09E+02
300	0.09811	E	20.0	4.63E-08	1.30E-05	3.56E-03
1000	0.01456	E	20.0	6.87E-09	8.70E-06	7.90E-04
3000	0.00233	E	20.0	1.10E-09	1.90E-06	5.79E-04
10,000	0.00032	E	20.0	1.51E-10	4.60E-07	3.28E-04

Table I.12. AY Farm 16.7 m Vent @ 1699 m³/hr Plume Centerline Results Using AERMOD

Distance (m)	AERMOD 1-hr Average Conc. (µg/m ³)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	472.7809	A	1.0	2.23E-04	1.10E-15	2.03E+11
30	227.4074	A	1.0	1.07E-04	1.70E-04	6.31E-01
100	30.18453	A	1.0	1.42E-05	4.80E-04	2.97E-02
300	4.00267	A	1.0	1.89E-06	7.40E-05	2.55E-02
1000	0.25816	A	1.0	1.22E-07	7.10E-06	1.72E-02
3000	0.01817	A	1.0	8.58E-09	8.60E-07	9.97E-03
10,000	0.0032	A	1.0	1.51E-09	9.70E-08	1.56E-02
10	159.593	B	1.0	7.53E-05	2.40E-39	3.14E+34
30	128.0975	B	1.0	6.05E-05	6.40E-07	9.45E+01
100	20.09968	B	1.0	9.49E-06	5.90E-04	1.61E-02
300	3.21281	B	1.0	1.52E-06	1.60E-04	9.48E-03
1000	0.20132	B	1.0	9.50E-08	1.60E-05	5.94E-03
3000	0.01416	B	1.0	6.68E-09	2.00E-06	3.34E-03
10,000	0.00172	B	1.0	8.12E-10	2.20E-07	3.69E-03
10	43.34826	C	1.0	2.05E-05	0.00E+00	
30	50.54259	C	1.0	2.39E-05	7.10E-12	3.36E+06
100	11.83649	C	1.0	5.59E-06	3.80E-04	1.47E-02
300	2.09322	C	1.0	9.88E-07	3.10E-04	3.19E-03
1000	0.16212	C	1.0	7.65E-08	3.80E-05	2.01E-03
3000	0.01178	C	1.0	5.56E-09	5.40E-06	1.03E-03
10,000	0.0011	C	1.0	5.19E-10	8.40E-07	6.18E-04
10	7.36115	D	1.0	3.47E-06	0.00E+00	
30	10.82546	D	1.0	5.11E-06	1.40E-19	3.65E+13
100	4.59288	D	1.0	2.17E-06	8.50E-05	2.55E-02
300	0.86355	D	1.0	4.08E-07	4.50E-04	9.06E-04
1000	0.10363	D	1.0	4.89E-08	9.40E-05	5.20E-04
3000	0.00989	D	1.0	4.67E-09	1.80E-05	2.59E-04
10,000	0.00095	D	1.0	4.48E-10	3.50E-06	1.28E-04
10	728.185	E	1.0	3.93E-05	0.00E+00	
30	83.23201	E	1.0	3.85E-06	3.80E-09	1.01E+03
100	8.15462	E	1.0	5.75E-07	2.70E-04	1.01E+03
300	1.21858	E	1.0	1.13E-07	1.70E-04	2.13E-03
1000	0.24045	E	1.0	2.39E-08	3.80E-05	6.68E-04
3000	0.05066	E	1.0	5.25E-09	9.20E-06	6.29E-04
10,000	0.01112	E	1.0	3.44E-04	0.00E+00	5.70E-04

Table I.12 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	853.6032	F	1.0	4.03E-04	0.00E+00	
30	101.9568	F	1.0	4.81E-05	0.00E+00	
100	10.96316	F	1.0	5.17E-06	1.00E-24	5.17E+18
300	1.626	F	1.0	7.67E-07	5.60E-06	1.37E-01
1000	0.3214	F	1.0	1.52E-07	2.50E-04	6.07E-04
3000	0.07946	F	1.0	3.75E-08	9.10E-05	4.12E-04
10,000	0.01846	F	1.0	8.71E-09	2.40E-05	3.63E-04
10	433.5017	A	3.4	2.05E-04	3.20E-16	6.39E+11
30	70.52831	A	3.4	3.33E-05	4.90E-05	6.79E-01
100	6.39389	A	3.4	3.02E-06	1.40E-04	2.16E-02
300	0.73643	A	3.4	3.48E-07	2.20E-05	1.58E-02
1000	0.04687	A	3.4	2.21E-08	2.10E-06	1.05E-02
3000	0.00419	A	3.4	1.98E-09	2.50E-07	7.91E-03
10,000	0.00051	A	3.4	2.41E-10	2.80E-08	8.60E-03
10	396.4864	B	3.4	1.87E-04	7.60E-40	2.46E+35
30	70.5972	B	3.4	3.33E-05	1.90E-07	1.75E+02
100	6.31642	B	3.4	2.98E-06	1.70E-04	1.75E-02
300	0.96071	B	3.4	4.53E-07	4.70E-05	9.65E-03
1000	0.05768	B	3.4	2.72E-08	4.80E-06	5.67E-03
3000	0.00399	B	3.4	1.88E-09	5.80E-07	3.25E-03
10,000	0.00045	B	3.4	2.12E-10	6.50E-08	3.27E-03
10	165.8996	C	3.4	7.83E-05	0.00E+00	
30	41.34351	C	3.4	1.95E-05	2.10E-12	9.29E+06
100	3.97558	C	3.4	1.88E-06	1.10E-04	1.71E-02
300	0.65599	C	3.4	3.10E-07	9.00E-05	3.44E-03
1000	0.04581	C	3.4	2.16E-08	1.10E-05	1.97E-03
3000	0.00318	C	3.4	1.50E-09	1.60E-06	9.38E-04
10,000	0.00025	C	3.4	1.18E-10	2.50E-07	4.72E-04
10	38.33231	D	3.4	1.42E-05	0.00E+00	
30	16.04348	D	3.4	1.22E-05	0.00E+00	
100	1.92435	D	3.4	1.81E-05	0.00E+00	
300	0.29482	D	3.4	7.57E-06	4.10E-20	1.85E+14
1000	0.02889	D	3.4	9.08E-07	2.50E-05	3.63E-02
3000	0.00237	D	3.4	1.39E-07	1.30E-04	1.07E-03
10,000	0.00017	D	3.4	1.36E-08	2.80E-05	4.87E-04

Table I.12 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	152.5365	E	3.4	7.20E-05	0.00E+00	
30	17.40506	E	3.4	8.21E-06	0.00E+00	
100	1.69602	E	3.4	8.00E-07	1.10E-09	7.28E+02
300	0.24997	E	3.4	1.18E-07	7.90E-05	1.49E-03
1000	0.04704	E	3.4	2.22E-08	5.10E-05	4.35E-04
3000	0.00891	E	3.4	4.21E-09	1.10E-05	3.82E-04
10,000	0.00161	E	3.4	7.60E-10	2.70E-06	2.81E-04
10	137.2895	F	3.4	6.48E-05	0.00E+00	
30	16.37894	F	3.4	7.73E-06	0.00E+00	
100	1.75409	F	3.4	8.28E-07	3.10E-25	2.67E+18
300	0.25725	F	3.4	1.21E-07	1.60E-06	7.59E-02
1000	0.04906	F	3.4	2.32E-08	7.50E-05	3.09E-04
3000	0.01123	F	3.4	5.30E-09	2.70E-05	1.96E-04
10,000	0.00228	F	3.4	1.08E-09	7.20E-06	1.49E-04
10	98.76446	G	3.4	4.66E-05	0.00E+00	
30	13.11696	G	3.4	6.19E-06	0.00E+00	
100	1.60747	G	3.4	7.59E-07	0.00E+00	
300	0.25711	G	3.4	1.21E-07	3.30E-13	3.68E+05
1000	0.0385	G	3.4	1.82E-08	2.10E-05	8.65E-04
3000	0.01059	G	3.4	5.00E-09	4.30E-05	1.16E-04
10,000	0.00347	G	3.4	1.64E-09	1.60E-05	1.02E-04
10	73.97981	C	10.0	3.49E-05	0.00E+00	
30	8.80636	C	10.0	4.16E-06	7.20E-13	5.77E+06
100	0.77188	C	10.0	3.64E-07	3.80E-05	9.59E-03
300	0.12738	C	10.0	6.01E-08	3.10E-05	1.94E-03
1000	0.00928	C	10.0	4.38E-09	3.80E-06	1.15E-03
3000	0.00079	C	10.0	3.73E-10	5.40E-07	6.90E-04
10,000	0.00006	C	10.0	2.83E-11	8.40E-08	3.37E-04
10	70.45476	D	10.0	3.33E-05	0.00E+00	
30	8.51964	D	10.0	4.02E-06	1.40E-20	2.87E+14
100	0.74403	D	10.0	3.51E-07	8.60E-06	4.08E-02
300	0.12054	D	10.0	5.69E-08	4.50E-05	1.26E-03
1000	0.01027	D	10.0	4.85E-09	9.40E-06	5.16E-04
3000	0.00078	D	10.0	3.68E-10	1.80E-06	2.05E-04
10,000	0.00005	D	10.0	2.36E-11	3.50E-07	6.74E-05

Table I.12 (cont.)

Distance (m)	AERMOD 1-hr Average Conc. ($\mu\text{g}/\text{m}^3$)	Stab Class	Wind Speed (m/sec)	AERMOD Conc. Fraction	Droppo Conc. Fraction	Ratio: AERMOD to Droppo
10	50.29871	E	10.0	2.37E-05	0.00E+00	
30	6.25477	E	10.0	2.95E-06	0.00E+00	
100	0.61411	E	10.0	2.90E-07	3.80E-10	7.63E+02
300	0.09346	E	10.0	4.41E-08	2.70E-05	1.63E-03
1000	0.01681	E	10.0	7.93E-09	1.70E-05	4.67E-04
3000	0.00293	E	10.0	1.38E-09	3.80E-06	3.64E-04
10,000	0.00044	E	10.0	2.08E-10	9.20E-07	2.26E-04
10	30.71719	C	20.0	1.45E-05	0.00E+00	
30	3.39214	C	20.0	1.60E-06	3.60E-13	4.45E+06
100	0.2963	C	20.0	1.40E-07	1.90E-05	7.36E-03
300	0.04914	C	20.0	2.32E-08	1.50E-05	1.55E-03
1000	0.00357	C	20.0	1.68E-09	1.90E-06	8.87E-04
3000	0.00025	C	20.0	1.18E-10	2.70E-07	4.37E-04
10,000	0.00003	C	20.0	1.42E-11	4.20E-08	3.37E-04
10	28.60266	D	20.0	1.35E-05	0.00E+00	
30	3.16155	D	20.0	1.49E-06	7.00E-21	2.13E+14
100	0.27568	D	20.0	1.30E-07	4.30E-06	3.03E-02
300	0.04505	D	20.0	2.13E-08	2.30E-05	9.24E-04
1000	0.00414	D	20.0	1.95E-09	4.70E-06	4.16E-04
3000	0.00035	D	20.0	1.65E-10	9.10E-07	1.82E-04
10,000	0.00002	D	20.0	9.44E-12	1.80E-07	5.24E-05
10	3.07484	E	20.0	9.97E-06	0.00E+00	
30	0.30739	E	20.0	1.45E-06	0.00E+00	
100	0.04702	E	20.0	1.45E-07	1.90E-10	7.64E+02
300	0.00839	E	20.0	2.22E-08	1.30E-05	1.71E-03
1000	0.00144	E	20.0	3.96E-09	8.70E-06	4.55E-04
3000	0.0002	E	20.0	6.80E-10	1.90E-06	3.58E-04
10,000	15.13637	E	20.0	9.44E-11	4.60E-07	2.05E-04

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