

**Smoke Plume Trajectory from In Situ Burning of
Crude Oil in Alaska --- Field Experiments and
Modeling of Complex Terrain**

Kevin B. McGrattan
Howard R. Baum
William D. Walton
Javier Trelles

Smoke Plume Trajectory from In Situ Burning of Crude Oil in Alaska --- Field Experiments and Modeling of Complex Terrain

Kevin B. McGrattan
Howard R. Baum
William D. Walton
Javier Trelles

January 1997



U.S. Department of Commerce
Michael Kantor, *Secretary*
National Institute of Standards and Technology
Arati Prabhakar, *Director*



U.S. Department of the Interior
Bruce Babbitt, *Secretary*
Minerals Management Service
Thomas R. Fry, *Director*



Alaska Department of Environmental Conservation
Michele Brown, *Commissioner*
Division of Spill Prevention and Response
Kurt Fredriksson, *Director*

**Smoke Plume Trajectory from *In Situ* Burning of Crude Oil in Alaska
Field Experiments and Modeling of Complex Terrain**

Kevin B. McGrattan, Howard R. Baum, William D. Walton and Javier Trelles
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

Abstract

A combination of numerical modeling and large scale experimentation has yielded a tremendous amount of information about the structure, trajectory and composition of smoke plumes from large crude oil fires. The model, ALOFT (A Large Outdoor Fire plume Trajectory), is based on the fundamental conservation equations that govern the introduction of hot gases and particulate matter from a large fire into the atmosphere. Two forms of the Navier-Stokes equations are solved numerically — one to describe the plume rise in the first kilometer, the other to describe the plume transport over tens of kilometers of complex terrain. Each form of the governing equations resolves the flow field at different length scales. Particulate matter, or any non-reacting combustion product, is represented by Lagrangian particles that are advected by the fire-induced flow field. Background atmospheric motion is described in terms of the angular fluctuation of the prevailing wind, and represented by random perturbations to the mean particle paths. Results of the model are compared with three sets of field experiments. Estimates are made of distances from the fire where ground level concentrations of the combustion products fall below regulatory threshold levels.

Executive Summary

A combination of numerical modeling and large scale experimentation has yielded a tremendous amount of information about the structure, trajectory and composition of smoke plumes from large crude oil fires. The model, ALOFT (A Large Outdoor Fire plume Trajectory), is based on the fundamental conservation equations that govern the introduction of hot gases and particulate matter into the atmosphere. Some major results of the ALOFT modeling effort and the experimental burns can be summarized as follows:

1. The results of the original plume modeling study, Reference [1], remain valid for flat terrain applications. "Flat" in this context refers to terrain that does not vary in height by more than about 10% of the expected plume height. Thus, for a single burn consuming up to about 1,000 barrels per hour in wind speeds less than 12 m/s (23 knots), the maximum ground level extent of the region where the concentration of PM-10 particulate would be in excess of $150 \mu\text{g}/\text{m}^3$ (hour-averaged) is roughly 5 km (3.0 miles) over flat terrain.
2. The ALOFT model has been extended to accommodate scenarios involving both flat and complex terrain, and the conclusions of Reference [1] have been expanded. The maximum extent of the region where the hour-averaged, ground level PM-10 particulate concentration would be in excess of $150 \mu\text{g}/\text{m}^3$ downwind of a burn consuming 1,000 barrels per hour can be as low as 1 km for a scenario with flat terrain and nearly adiabatic lapse rates, and as high as 20 km for a scenario where the terrain height extends above the mixing layer. More refined predictions for intermediate cases are included in the report. Also included are simple formulae for modifying the maximum ground level distances to accommodate changes in air quality thresholds and combustion product emission factors.
3. The uncertainty of ALOFT model predictions is largely a function of the uncertainty in the meteorological conditions and fire emission rates. The factor of safety of 2 that had been applied to the downwind distance predictions as an estimate of uncertainty for the original flat terrain modeling results has been replaced by more appropriate ways of assessing uncertainty, and these will be presented in the report.
4. The ventilation factor, which is the product of the wind speed and mixing layer depth used to characterize the dispersive potential of the atmosphere, is a reasonably good indicator of expected ground level concentration of smoke or combustion products from a large burn. This is true of both flat and complex terrain.
5. Smoke particulate is by far the most likely combustion product of crude oil burning to exceed ambient air quality standards at ground level beyond a few hundred meters from the fire.
6. Peak concentrations of ground level smoke particulate for the 1993 Newfoundland Offshore Burn Experiment, the 1994 Alaska Clean Seas Burning of Emulsions experiment, and the 1994 diesel fuel burns in Mobile, Alabama, never exceeded $100 \mu\text{g}/\text{m}^3$ beyond a few hundred meters from the fires, and in most cases were well below that level.

Contents

1	Introduction	1
2	Description of the ALOFT Model	3
2.1	Historical Background	3
2.2	Development of the ALOFT model	3
2.3	ALOFT Compared to Other Dispersion Models	5
3	The Fire and its Emissions	7
3.1	Heat Release Rate	7
3.2	Particulate Emissions	8
3.3	Particulate Size	11
3.4	Other Emissions	12
4	The Smoke Plume	15
4.1	The Boussinesq Approximation	15
4.2	Scaling Laws for the Three-Dimensional Equations (ALOFT-CT)	17
4.3	Scaling Laws for the Two-Dimensional Equations (ALOFT-FT)	18
4.4	Atmospheric Turbulence	20
4.5	Flat Terrain Correlations	24
5	Validation Experiments for ALOFT-FT	29
5.1	The Newfoundland Offshore Burn Experiment (NOBE)	29
5.2	Alaska Clean Seas Burning of Emulsions Experiment	33
5.3	Mesoscale Diesel Fuel Burns, Mobile, Alabama	37
5.4	Discussion of Field Experiments	46
6	ALOFT Applications in Alaska	50
6.1	Outline of the Solution Procedure	50
6.2	Single Burn, Single Sounding, Various Locations	52
6.2.1	North Slope, Atigun Pass and Fairbanks	53
6.2.2	Port Valdez	58
6.2.3	Prince William Sound	58
6.2.4	Cook Inlet	61
6.3	Single Burn, Various Soundings, Single Location	61
6.4	Multiple Burns, Various Soundings, Various Locations	68
6.5	Ground Level Distance Estimates for Complex Terrain	70
7	Conclusions	77
8	Acknowledgements	79
9	References	80
	Appendices	84

A	Description of ALOFT Model Input Parameters	84
A.1	Burn Input Parameters	84
A.2	Meteorological Input Parameters	86
A.3	Numerical Grid Parameters	87
A.4	Processing Results	88
A.5	Forecast Systems Laboratory (FSL) sounding format	88
B	Numerical Method	90
B.1	ALOFT-FT Algorithm (Plume Rise Calculation for ALOFT-CT)	90
B.1.1	The Energy Equation	90
B.1.2	The Momentum Equations	91
B.1.3	The Incompressibility Condition	93
B.1.4	Particle Tracking	94
B.2	ALOFT-CT Wind Field Calculation	94
B.2.1	The Energy Equation	95
B.2.2	The Momentum Equations	96
B.2.3	The Incompressibility Condition	97
B.2.4	Particle Tracking	98
C	Additional Results and Flat Terrain Wind Speed/Lapse Rate Charts	100

List of Figures

1	Near-field simultaneous measurements of particulate and CO ₂ at the 1994 Alaska Clean Seas emulsion burns.	9
2	Near-field simultaneous measurements of particulate and CO ₂ at the 1994 Mobile diesel fuel burn.	10
3	Electron micrograph of a smoke particle from a 3 m crude oil fire.	12
4	Three dimensional view of a computed smoke plume in the first few kilometers of its development.	21
5	A view of the plume from below.	21
6	Photograph taken from about 200 m downwind of the Newfoundland Offshore Burn Experiment (NOBE) showing the two large counter-rotating vortices which characterize the structure of the rising smoke plume.	22
7	Correlated ALOFT-FT results for an 820 MW fire and typical overland wind fluctuations.	25
8	Average temperature lapse rate versus mixing layer depth for a variety of soundings in Alaska.	28
9	Photograph of the Newfoundland Offshore Burn Experiment showing the shift of the wind at about 120 m off the surface.	29
10	Cross sectional slices of the simulated smoke plume from the second NOBE burn.	31
11	Cross sectional slices of the actual smoke plume from the second NOBE burn.	32
12	Lidar measurement of plume centerline of the second burn taken from University of Washington airplane.	33
13	Aerial photograph taken of the second ACS burn, Prudhoe Bay, September, 1994.	34
14	ALOFT predictions of ground level particulate concentrations along side the actual time-averaged RAM data for the three ACS Emulsion Burns.	36
15	Ground level particulate concentration about 1 km directly downwind of the second ACS burn.	37
16	Downwind view of the simulated smoke plume from the second ACS emulsion burn, Prudhoe Bay, September, 1994.	38
17	Photograph of a diesel fuel burn at the US Coast Guard Fire and Safety Test Detachment, Mobile, Alabama.	39
18	ALOFT predictions of maximum ground level particulate concentration for the Mobile burn series of October, 1994.	40
19	Cross-plume flight paths for burn 2.	42
20	Cross-plume flight paths for burn 3.	43
21	Lidar images of the plume cross section for the morning burn of October 26, 1994, Mobile Bay.	44
22	Lidar images of the plume cross section for the afternoon burn of October 26, 1994, Mobile Bay.	45
23	ALOFT predictions of ground level particulate concentration for the morning burn of October 26, 1994, in Mobile Bay.	47
24	ALOFT predictions of ground level particulate concentration for the afternoon burn of October 26, 1994, in Mobile Bay.	48

25	Three-dimensional view of simulated smoke plume originating off Bligh Island, Prince William Sound.	51
26	Footprint of simulated smoke plume originating at Pump Station No. 1, Prudhoe Bay.	54
27	Footprint of simulated smoke plume originating at Pump Station 4, near Atigun Pass.	55
28	Footprint of simulated smoke plume originating at just a few kilometers south of Atigun Pass.	56
29	Footprint of simulated smoke plume originating near the Trans-Alaska Pipeline just east of Fairbanks.	57
30	Footprint of simulated smoke plume originating off Valdez Marine Terminal.	59
31	Footprint of simulated smoke plume originating in the Valdez Narrows.	60
32	Footprint of simulated smoke plume originating off Bligh Island.	62
33	Footprint of simulated smoke plume originating off Knowles Head.	63
34	Footprint of simulated smoke plume originating off Zaikof Point.	64
35	Footprint of simulated smoke plume originating off Bligh Reef.	65
36	Footprint of simulated smoke plume originating at Otter Creek on the Kenai Peninsula.	66
37	Footprint of simulated smoke plume originating off Harriet Point on the western shore of Cook Inlet.	67
38	Three-dimensional views of smoke plumes originating in the Valdez Narrows.	69
39	Footprint of simulated smoke plume from a single large fire originating near Pump Station 1, Prudhoe Bay.	71
40	Footprint of simulated smoke plume from 10 fires originating near Pump Station 1, Prudhoe Bay.	72
41	Footprint of simulated smoke plume from 10 fires originating near Pump Station 1, Prudhoe Bay.	73
42	Correlated ALOFT-FT results for a fire generating 1,336 MW with typical overland wind fluctuations.	101
43	Correlated ALOFT-FT results for a fire generating 2672 MW with typical overland wind fluctuations.	102
44	Correlated ALOFT-FT results for a fire generating 668 MW with typical overland wind fluctuations.	103
45	Footprint of simulated smoke plume originating in the Valdez Narrows.	104
46	Footprint of simulated smoke plume originating in the Valdez Narrows.	105
47	Footprint of simulated smoke plume originating in the Valdez Narrows.	106
48	Footprint of simulated smoke plume originating in the Valdez Narrows.	107
49	Footprint of simulated smoke plume originating in the Valdez Narrows.	108
50	Footprint of simulated smoke plume originating in the Valdez Narrows.	109
51	Footprint of simulated smoke plume originating in the Valdez Narrows.	110
52	Footprint of simulated smoke plume originating in the Valdez Narrows.	111
53	Footprint of simulated smoke plume originating in the Valdez Narrows.	112
54	Footprint of simulated smoke plume originating in the Valdez Narrows.	113
55	Footprint of simulated smoke plume originating in the Valdez Narrows.	114
56	Footprint of simulated smoke plume originating in the Valdez Narrows.	115

57	Footprint of simulated smoke plume originating at the Trans-Alaska Pipeline just west of Fairbanks.	116
58	Footprint of simulated smoke plume originating at the Trans-Alaska Pipeline just west of Fairbanks.	117
59	Footprint of simulated smoke plume originating at the Trans-Alaska Pipeline just west of Fairbanks.	118
60	Footprint of simulated smoke plume originating at the Trans-Alaska Pipeline just west of Fairbanks.	119
61	Footprint of simulated smoke plume originating at the Trans-Alaska Pipeline just west of Fairbanks.	120
62	Footprint of simulated smoke plume originating at the Trans-Alaska Pipeline just west of Fairbanks.	121
63	Footprint of six smoke plumes originating at the Valdez Marine Terminal.	122
64	Footprint of six smoke plumes originating at the Valdez Marine Terminal.	123
65	Footprint of six smoke plumes originating at the Valdez Marine Terminal.	124
66	Footprint of six smoke plumes originating at the Valdez Marine Terminal.	125
67	Footprint of six smoke plumes originating at the Valdez Marine Terminal.	126
68	Footprint of six smoke plumes originating at the Valdez Marine Terminal.	127

List of Tables

1	Emission factors and cumulative mass fraction for several particulate sizes.	11
2	US EPA National Ambient Air Quality Standards (NAAQS), Alaska State Regulatory Standards for Concentrations of Contaminants in the Ambient Air, plus relevant Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PEL).	13
3	Emission factors for the major combustion products from the Newfoundland Off-shore Burn Experiment.	14
4	Threshold levels for several combustion products compared with the equivalent levels of PM-10 particulate.	15
5	ALOFT Default Dispersion Parameters.	23
6	Key to Pasquill Stability Categories.	23
7	Summary of the ACS Mesoscale Emulsion Burns.	35
8	Summary of the Mobile Burn Series, October, 1994.	38
9	Distance from a fire consuming 1,000 bbl/h beyond which the hour-averaged ground level concentration of PM-10 falls below $150 \mu\text{g}/\text{m}^3$	75
10	Burning characteristics of several heavy hydrocarbon fuels.	86
11	ALOFT Default Dispersion Parameters.	87